A vision towards table-top hadron (not only) beams

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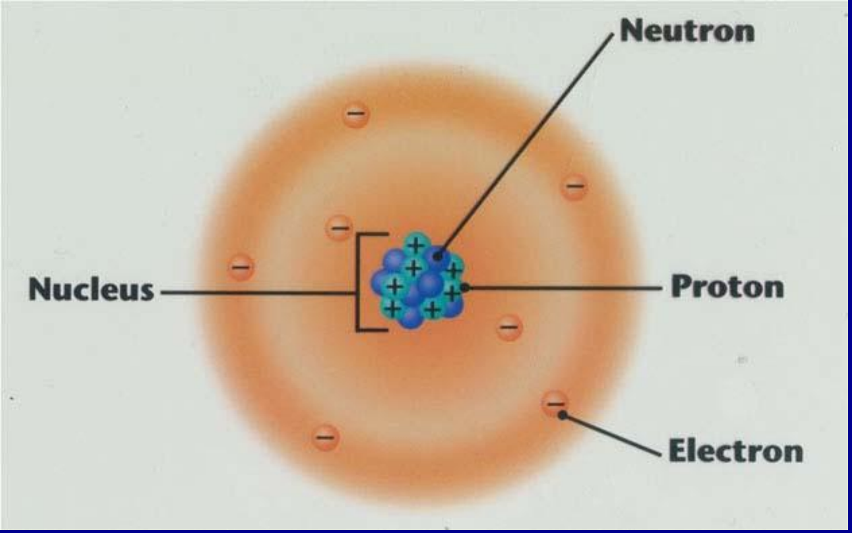
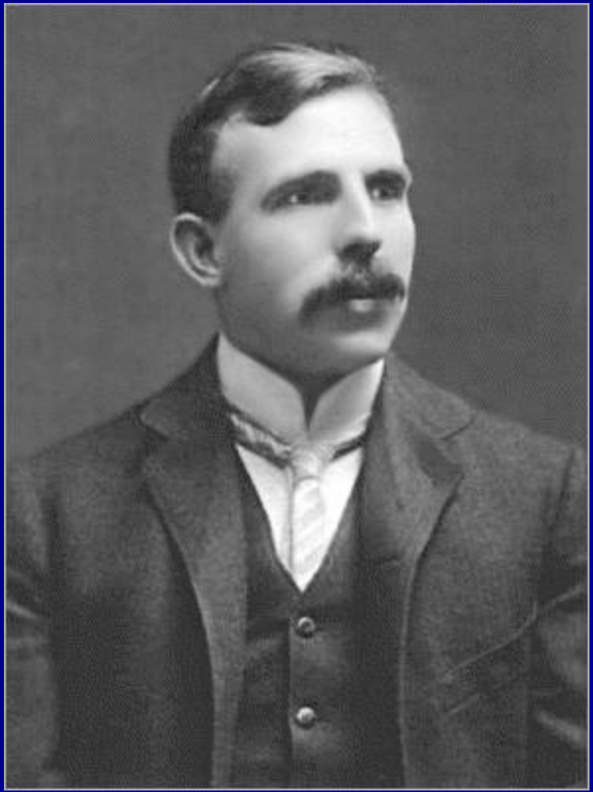
… about one hundred years ago …

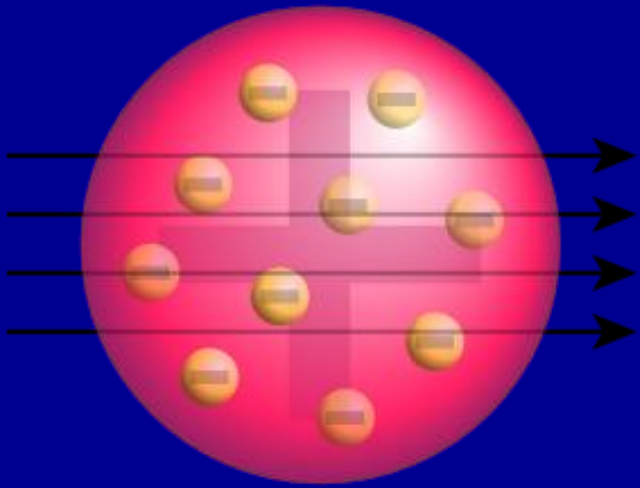
History and properties of protons

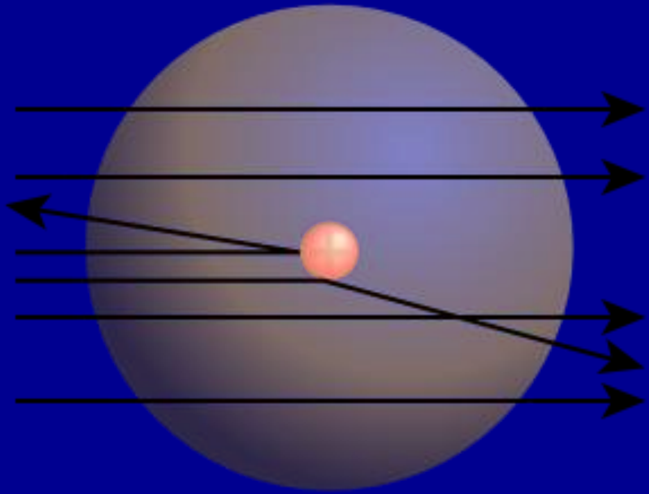
- Protons discovered by Ernest Rutherford in 1918.
- Neutron by Chadwick in 1932
- Electrons by Thomson in 1897
- Proton: Elementary particle as part of the nucleus
- 1836 time mass of electron but positively charged

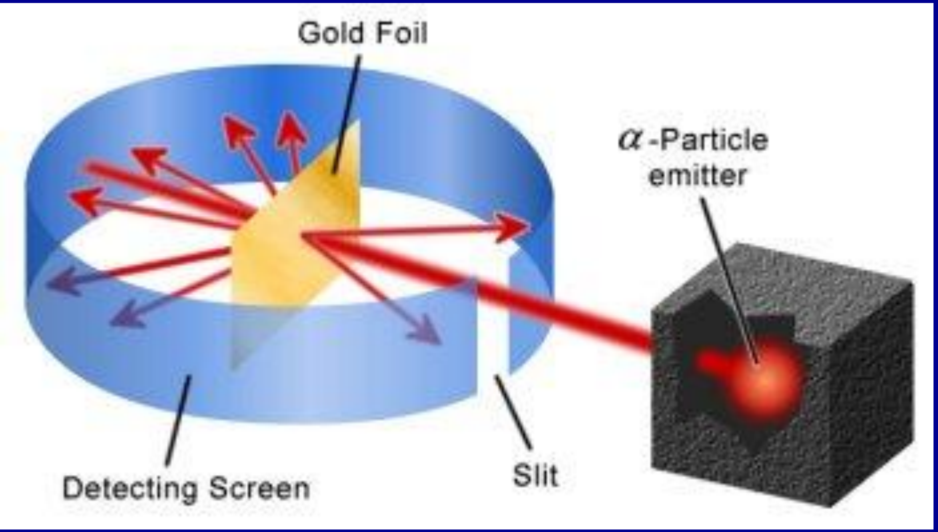


Discovery of proton 1896







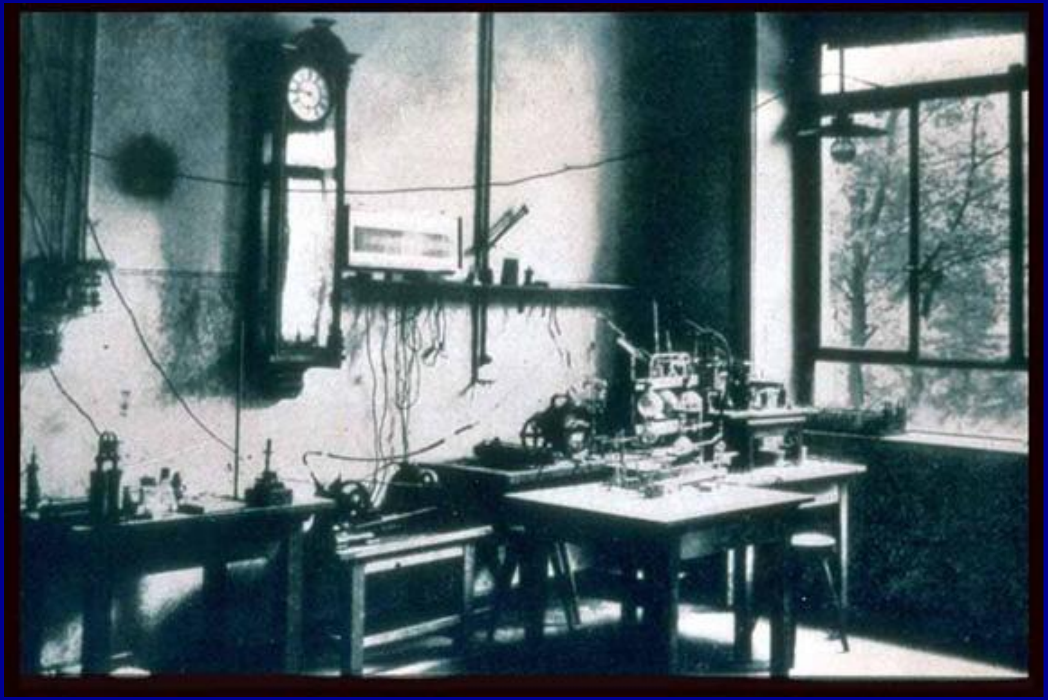


Rutherford Experiment:
Nuclear Atom

Discovery of X-Rays

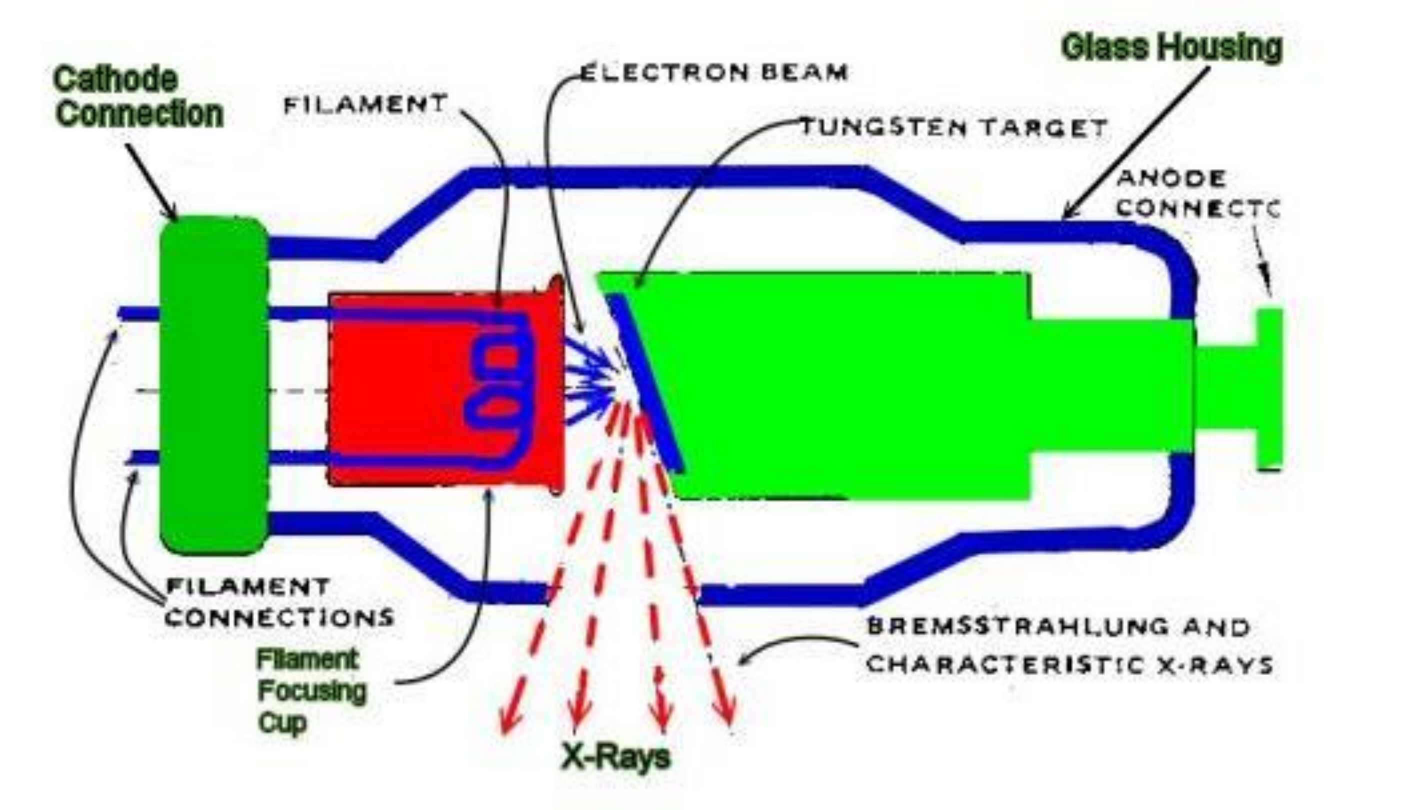
November 1895, Würzburg

Wilhelm Conrad Röntgen

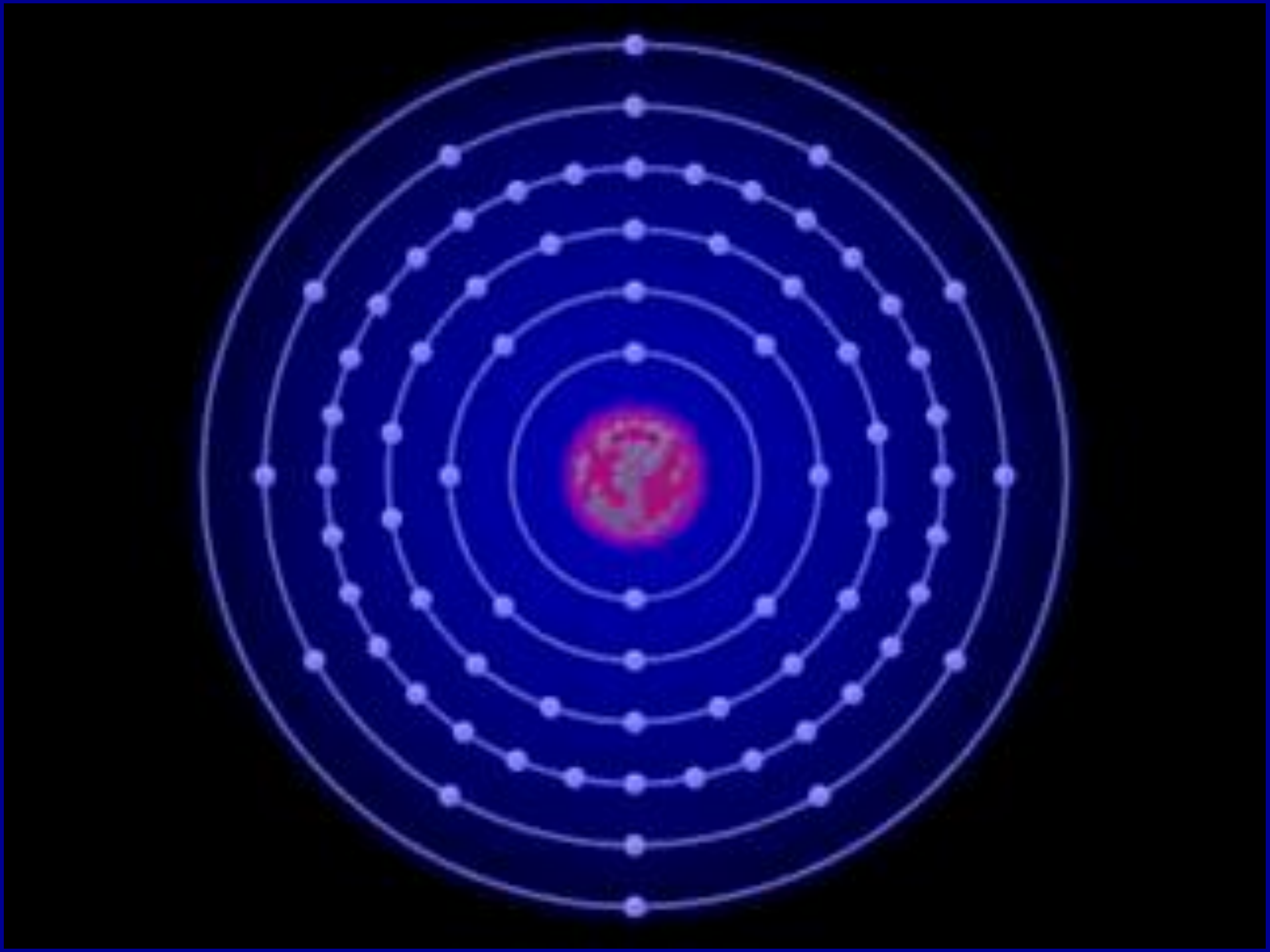


Roentgen's Wurzburg Laboratory

X-ray tubes



Cathode Connection
FILAMENT
ELECTRON BEAM
TUNGSTEN TARGET
Glass Housing
ANODE CONNECTO
FILAMENT CONNECTIONS
Filament Focusing Cup
X-Rays
BREMSSTRAHLUNG AND CHARACTERISTIC X-RAYS



Discovered by Heinrich Hertz in 1897 - Explained by Albert Einstein in 1905

Photoelectric Effect

PHOTOELECTRIC EFFECT

M. Mongkolsuk

11/04/2004

electrons can generate photons

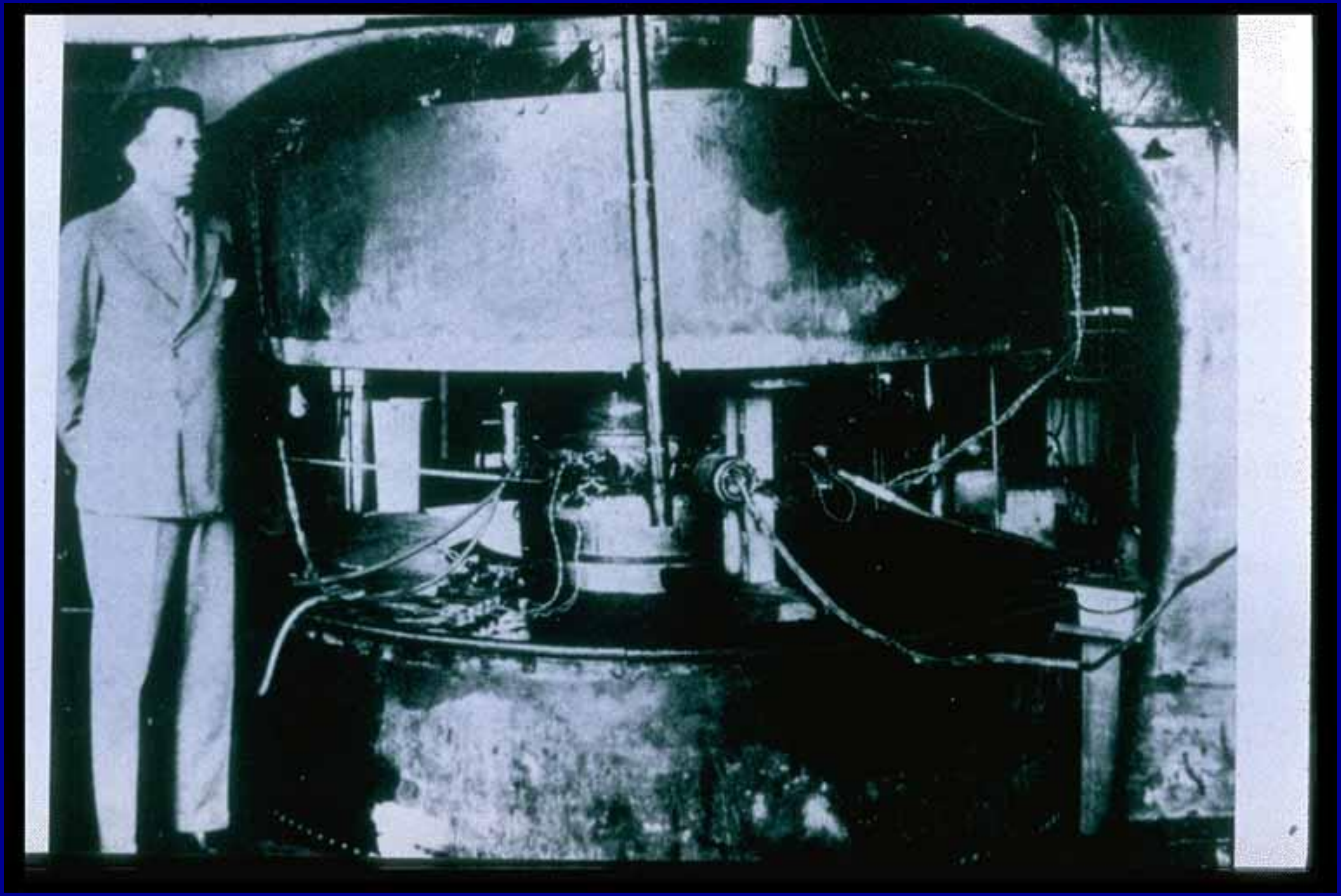
and

photons can generate electrons

- *ELECRON SOURCES*
- *PHOTON SOURCES*
- *PROTON SOURCES*

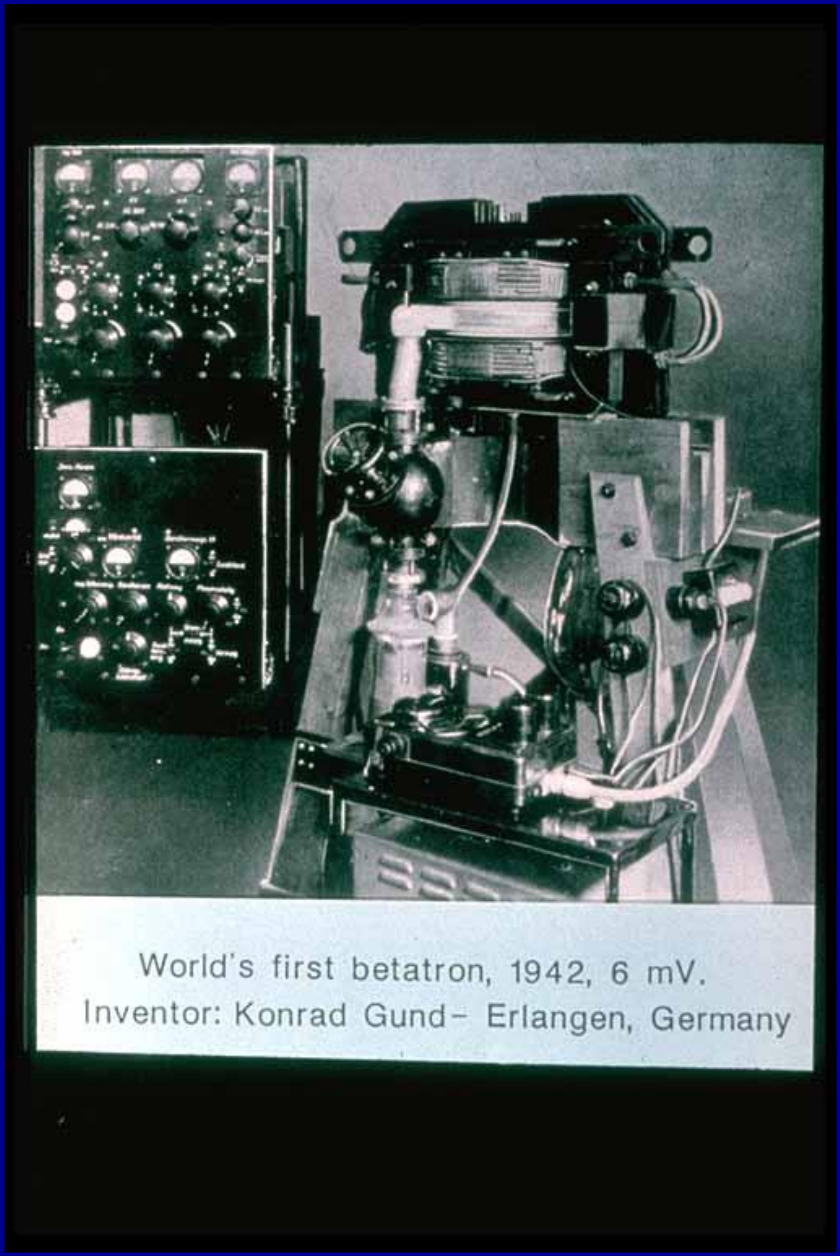
RELENTLESS EFFORT IN THE DEVELOPMENT OF ACCELERATOR TECHNOLOGY FOR

- *FUNDAMENTAL SCIENCES*
- *MEDICINE*
- *INDUSTRY*



1931 Ernest Lawrence, at the University of California first cyclotron capable of producing deuterons, protons, and alpha particles.

1940 - Donald Kerst, betatron, at the University of Illinois, accelerate electrons, first at 2.3 MeV and later to 300 MeV. Commercial vendors helped promote clinical applications of the new technology.

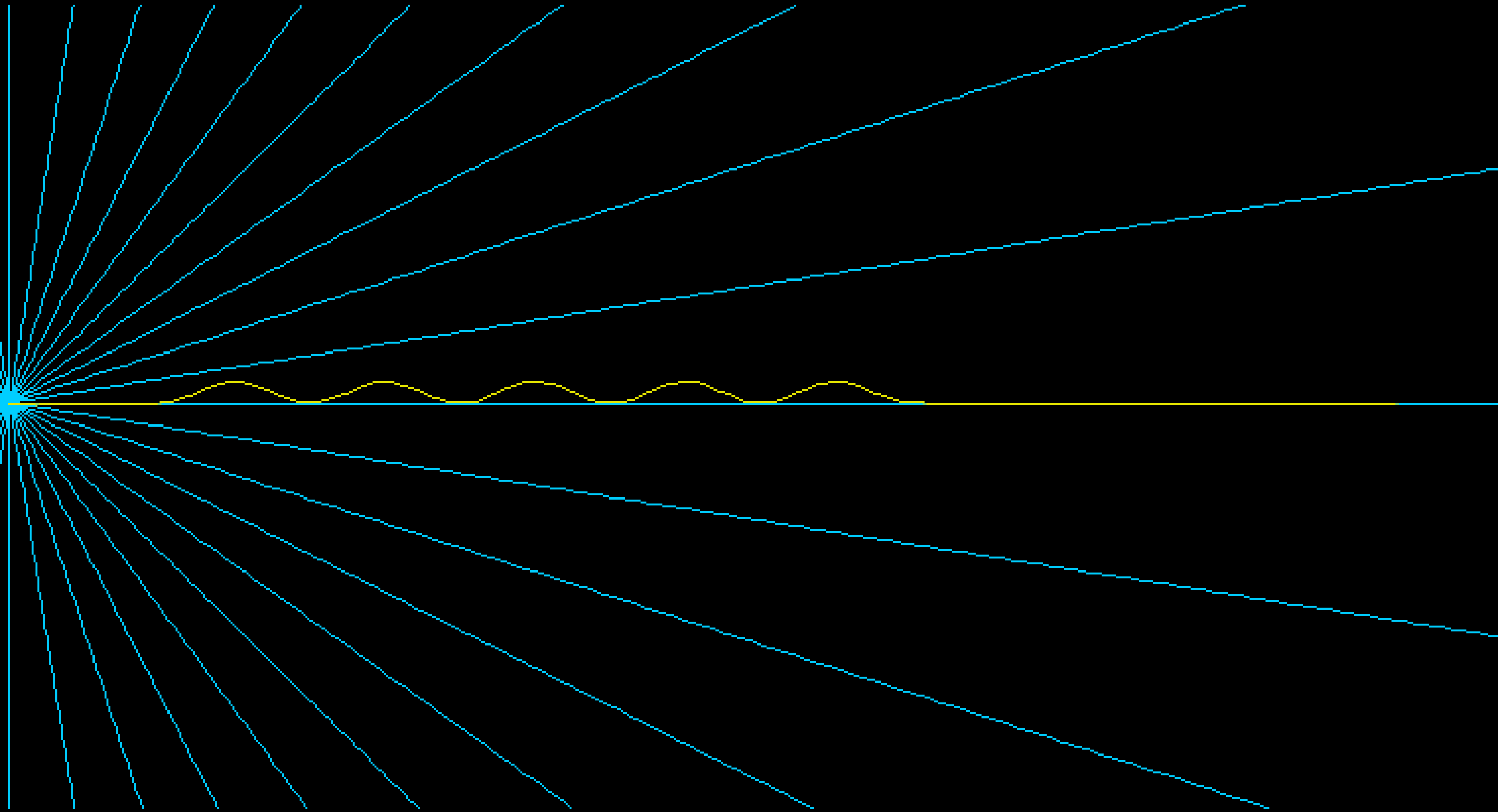


1942. First betatron in clinical use.

Although Kerst first developed the betatron in the U.S., it saw its first clinical application by Gund, using this machine in Germany during the war.

SYNCHROTRON RADIATION SOURCES

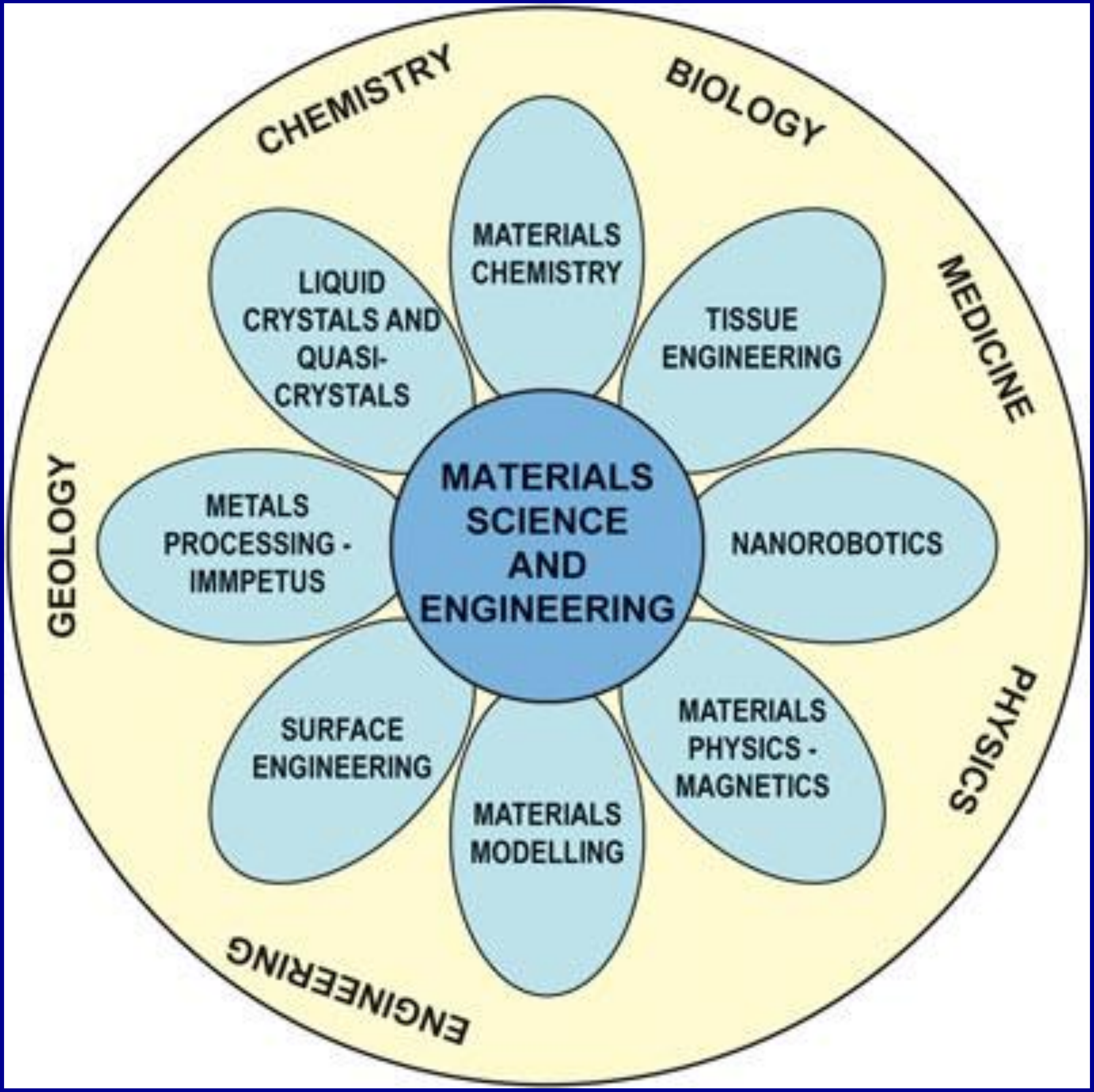
SYNCROTRON RADIATION



SYNCHROTRON LIGHT CENTERS IN THE WORLD

EUROPEAN SYNCHROTRON LIGHT SOURCE

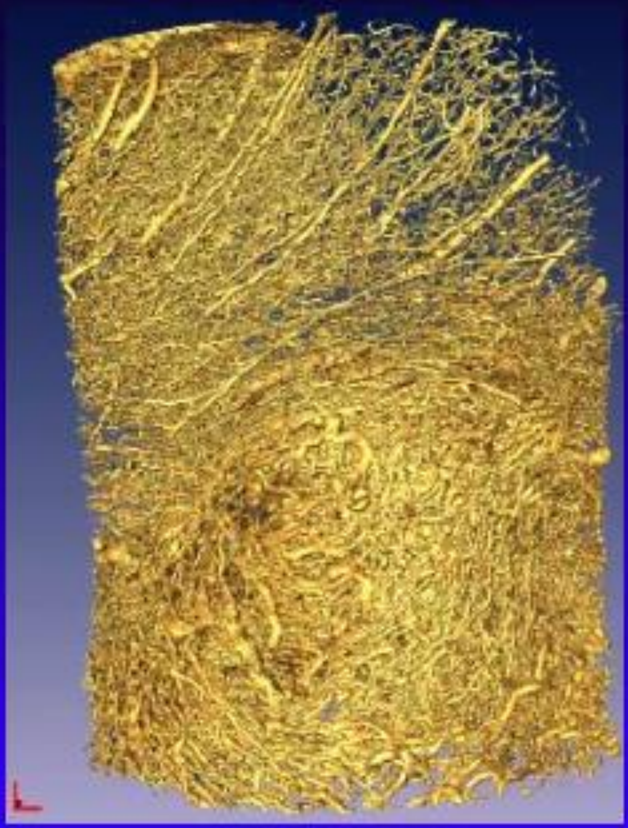
Grenoble FR


CHEMISTRY
BIOLOGY
MEDICINE
PHYSICS
ENGINEERING
GEOLOGY
MATERIALS SCIENCE AND ENGINEERING
MATERIALS CHEMISTRY
TISSUE ENGINEERING
NANOROBOTICS
MATERIALS PHYSICS - MAGNETICS
MATERIALS MODELLING
SURFACE ENGINEERING
METALS PROCESSING - IMMPETUS
LIQUID CRYSTALS AND QUASI-CRYSTALS

20.5 keV pixel 1.4 micron

bar= 0.1 mm

Monkey cortical vascular network

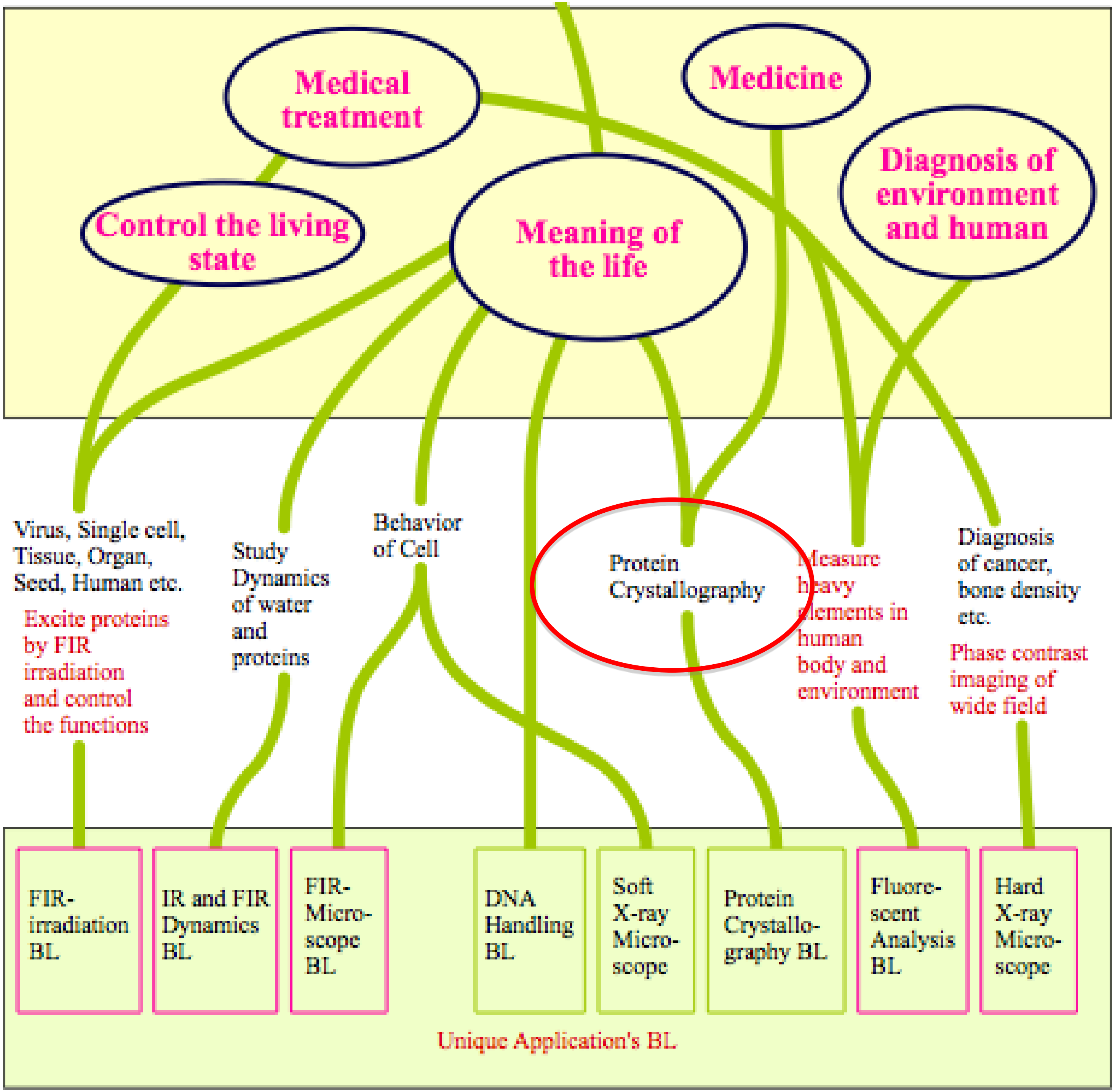


Implanted tumor cortical vascular network in rat cortex

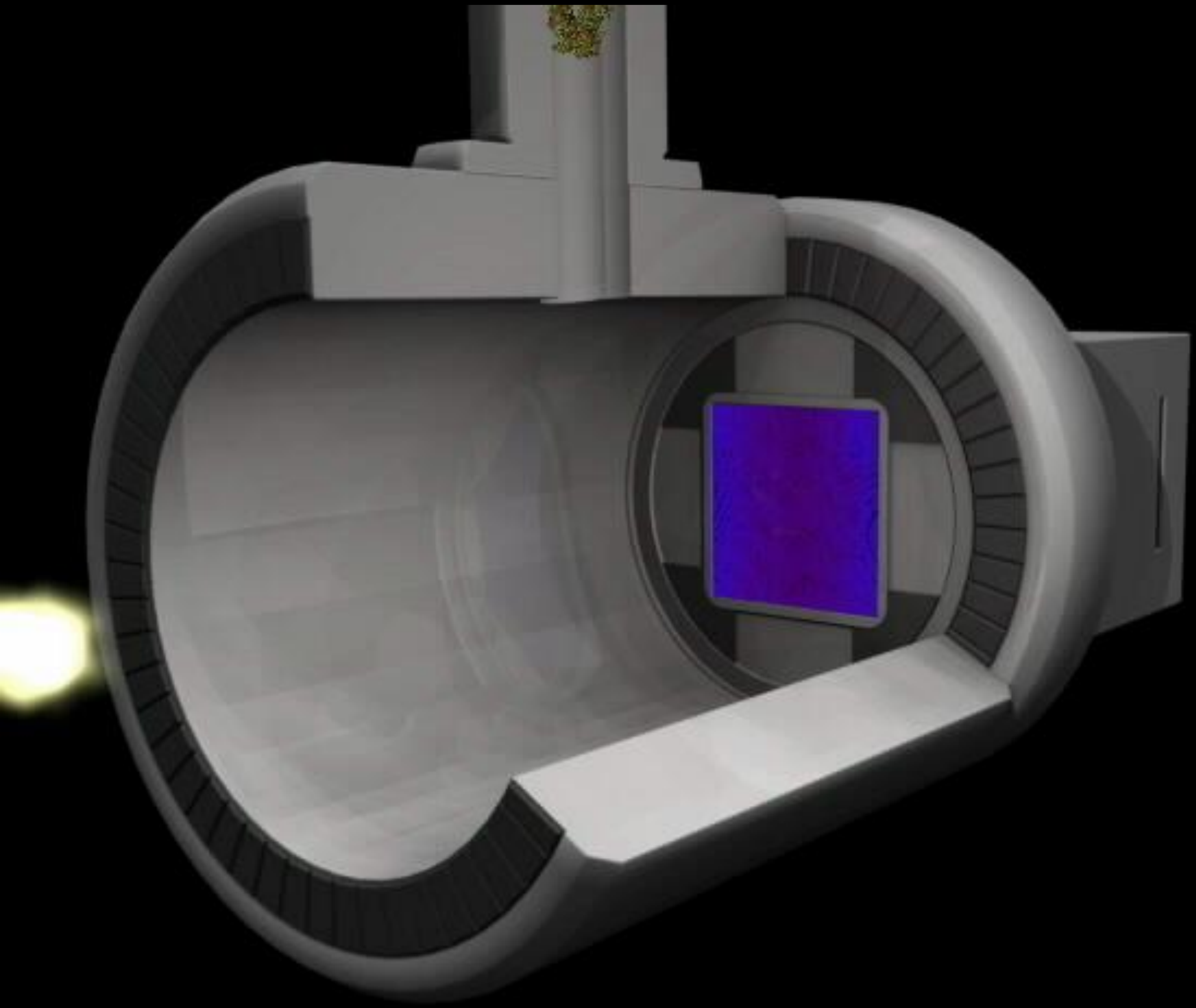
L. Risser et al. J. Cereb. Blood flow and Metabolism, 2006

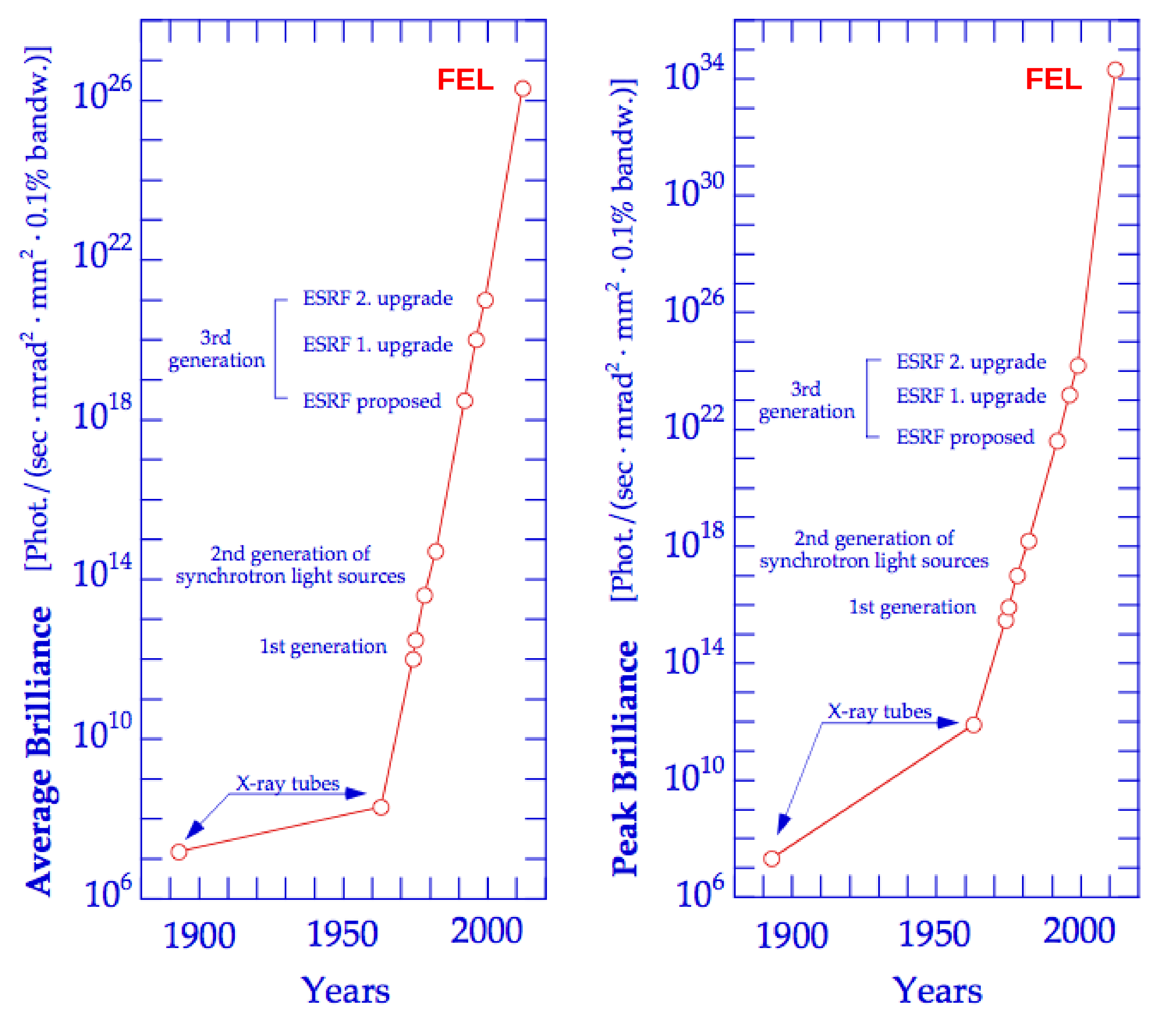
by courtesy of A. Bravin

ESRF



LIFE SCIENCE





FEL
ESRF 2. upgrade
ESRF 1. upgrade
ESRF proposed
3rd generation
2nd generation of synchrotron light sources
1st generation
X-ray tubes
Average Brilliance [Phot./(sec · mrad^2 · mm^2 · 0.1% bandw.)]
10^{26}
10^{22}
10^{18}
10^{14}
10^{10}
10^{6}
1900
1950
2000
Years
FEL
ESRF 2. upgrade
ESRF 1. upgrade
ESRF proposed
3rd generation
2nd generation of synchrotron light sources
1st generation
X-ray tubes
Peak Brilliance [Phot./(sec · mrad^2 · mm^2 · 0.1% bandw.)]
10^{34}
10^{30}
10^{26}
10^{22}
10^{18}
10^{14}
10^{10}
10^{6}
1900
1950
2000
Years

LARGE INFRASTRUCTURES

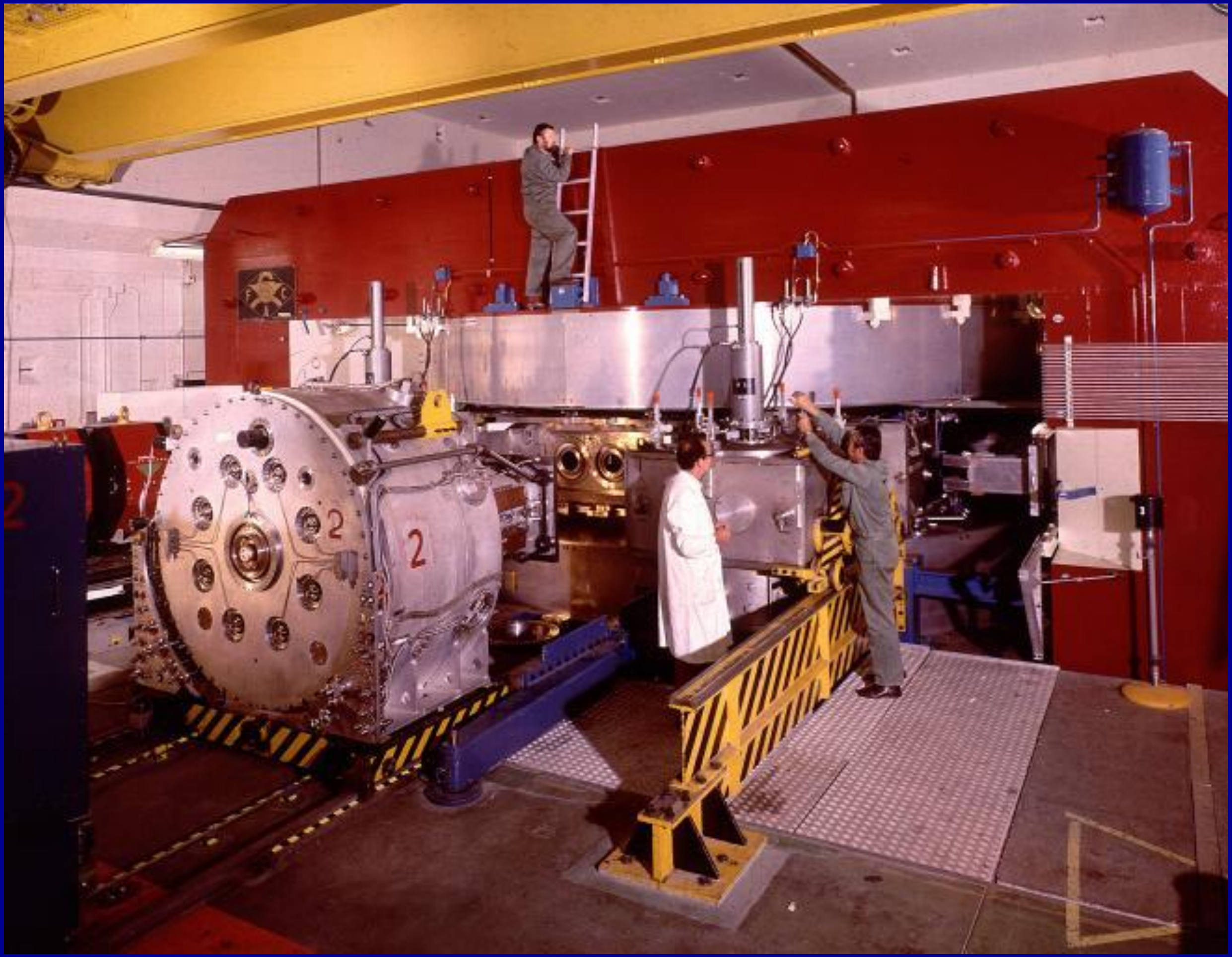
COSTS : 500 – 1000 MEuro

What technology for the future ?

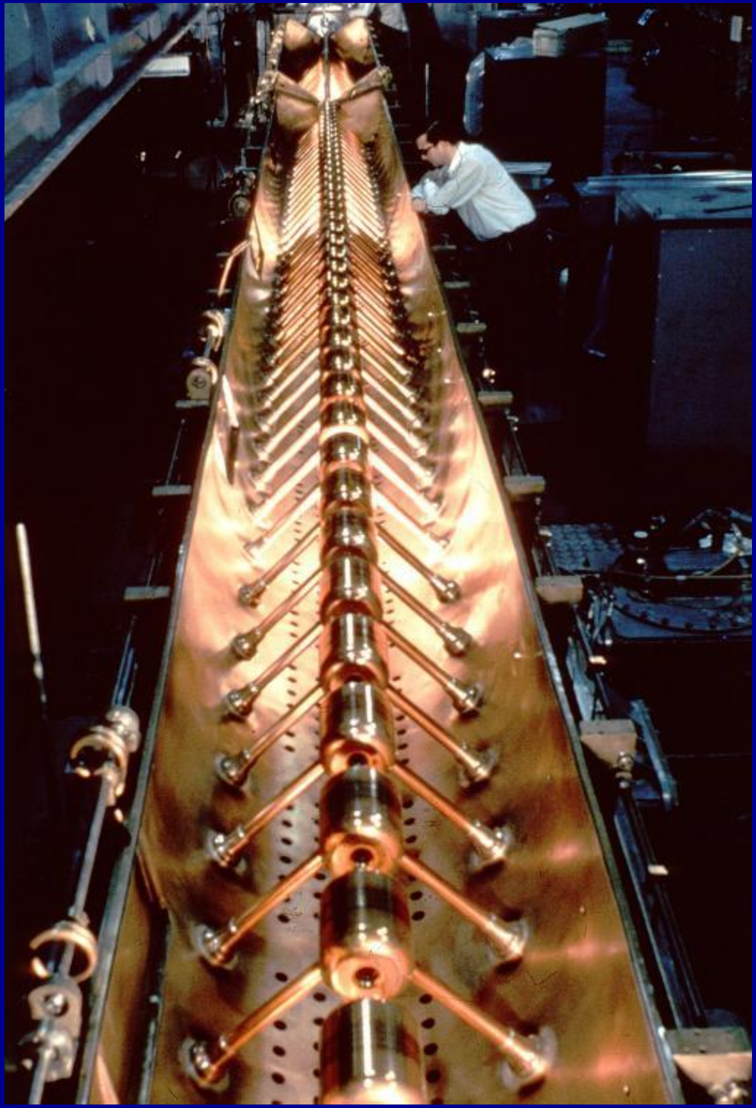
ACCELERATORS FOR HIGH ENERGY PHYSICS

Cockcroft-Walton Column. This 800 kV generator is used for the pre-acceleration of protons before injection into the linear accelerator (LINAC)

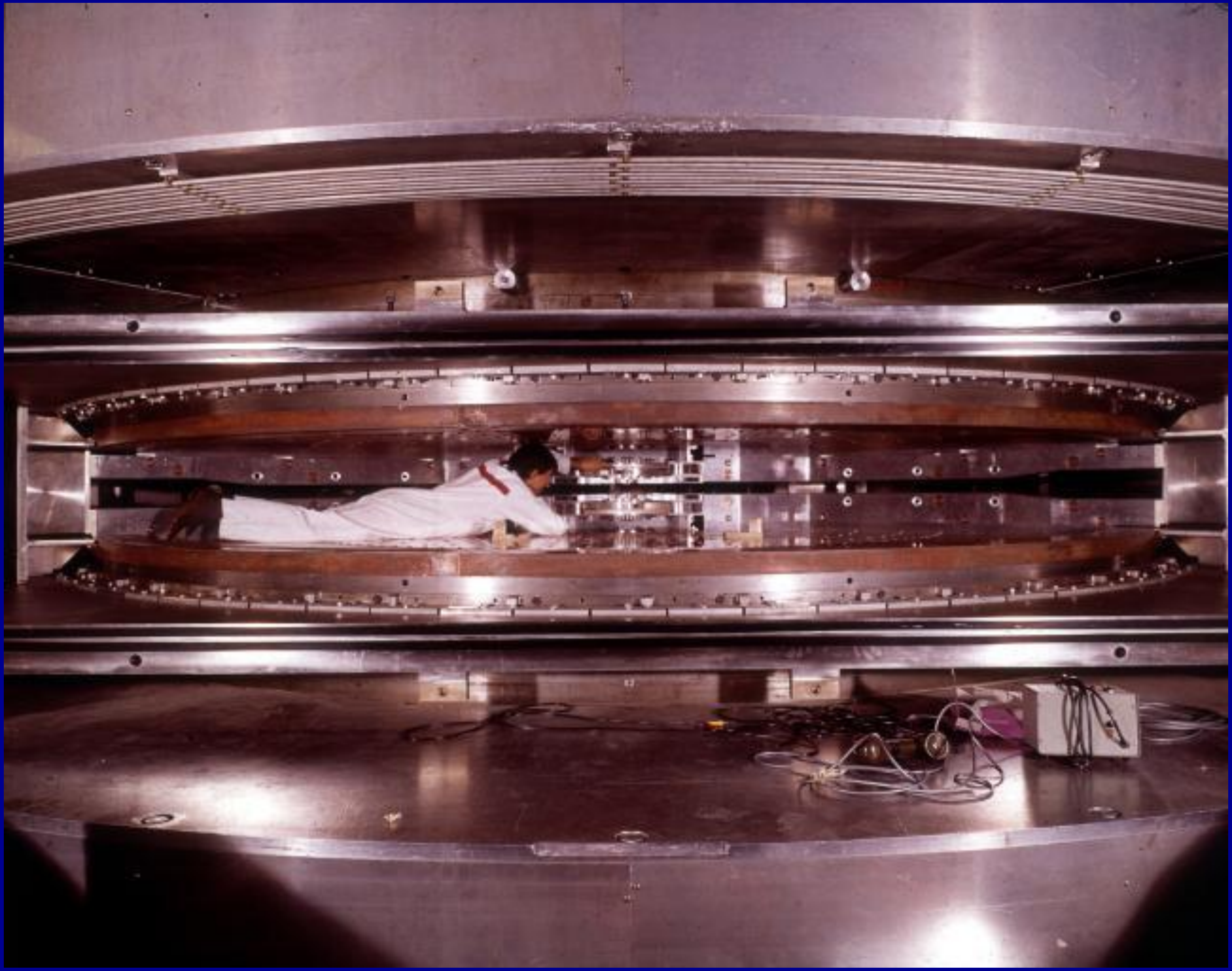
1957 - The 600 MeV SC (Synchro-Cyclotron), the CERN's first accelerator. It was closed in 1990.



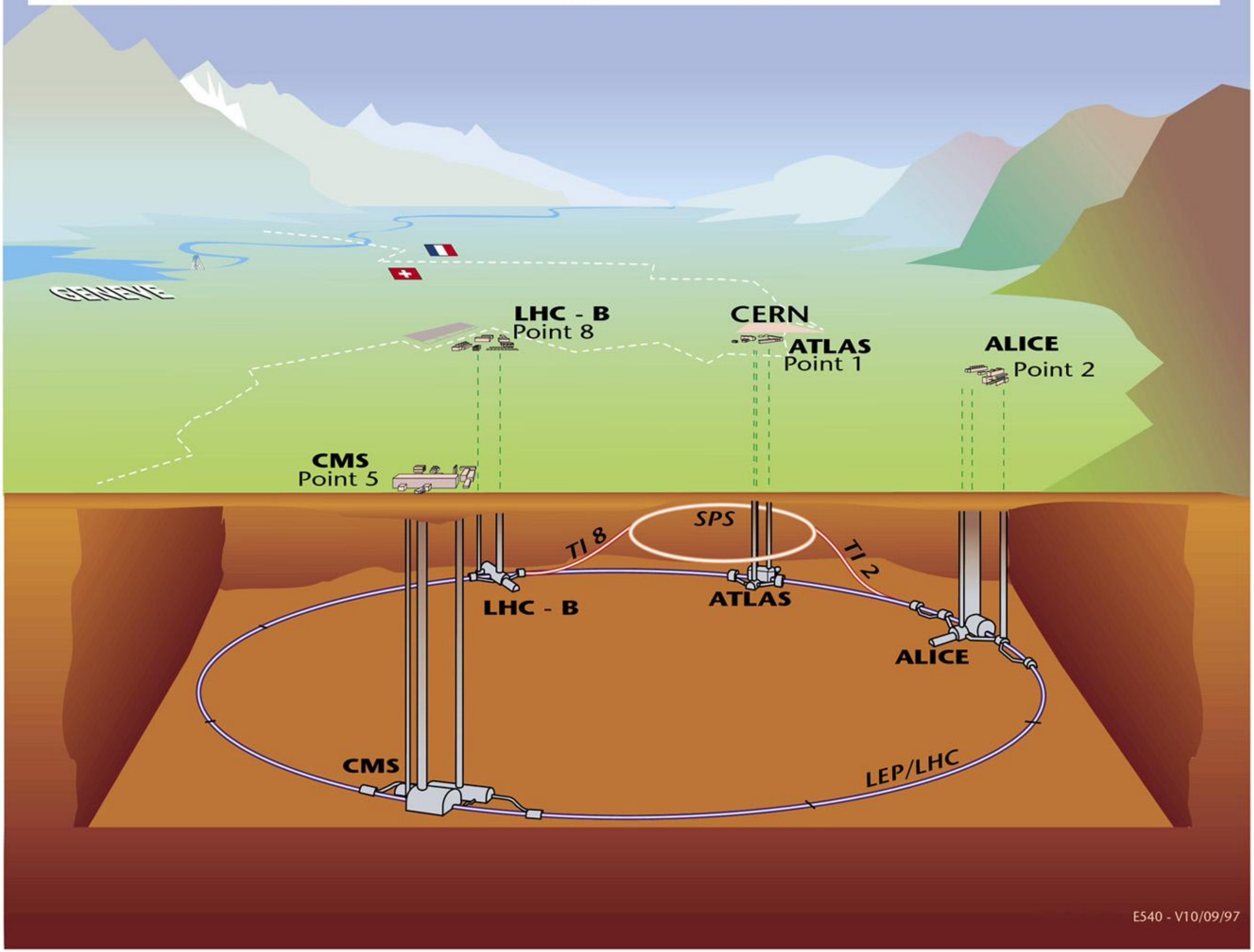
LINAC: Linear proton accelerator with an energy of 50 MeV



1974 - 600 MeV Synchro-Cyclotron for proton beams



Overall view of the LHC experiments.



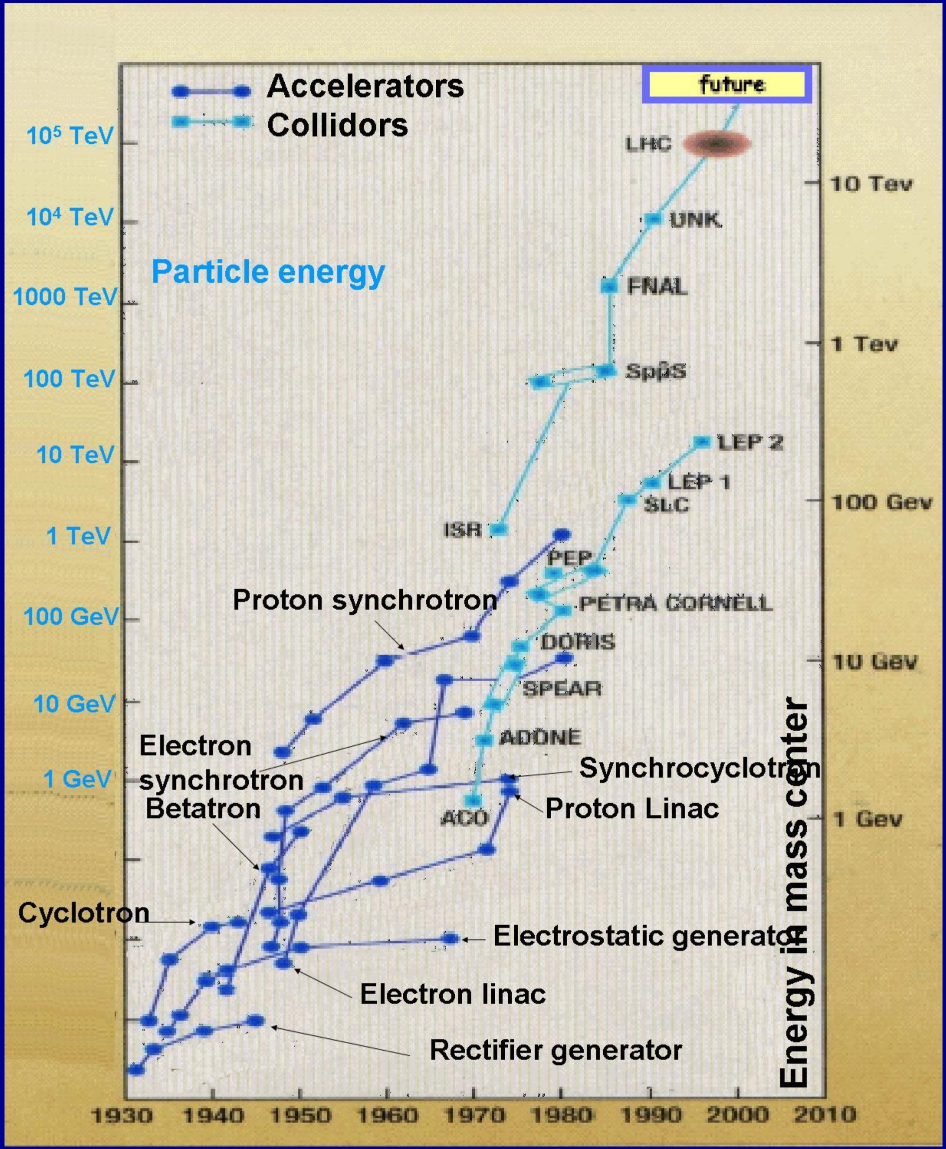
Particle accelerator evolution

About every 7 years

a new accelerator technology is invented

to increase particle energies

(continuous lines indicate same accelerator technology)



Proton accelerator are very large and expensive machines

- Large Hadron Collider (LHC), CERN 27 km circumference (LHC machine costs 3 billion Euro)

Ring: 27 km

What technology for the future ?

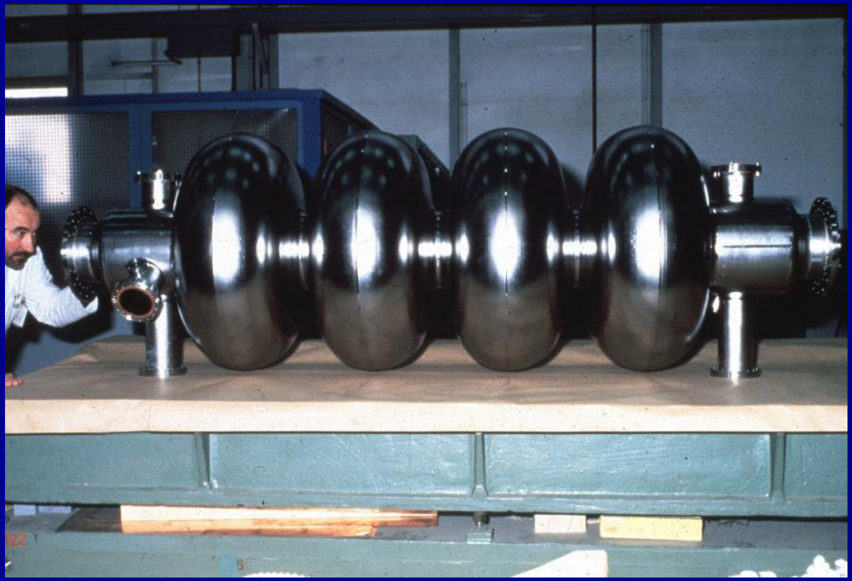
- SNS facility in the USA

- European Spallation Infrastructure (estimated 1 billion Euro)

Classical accelerator limitations

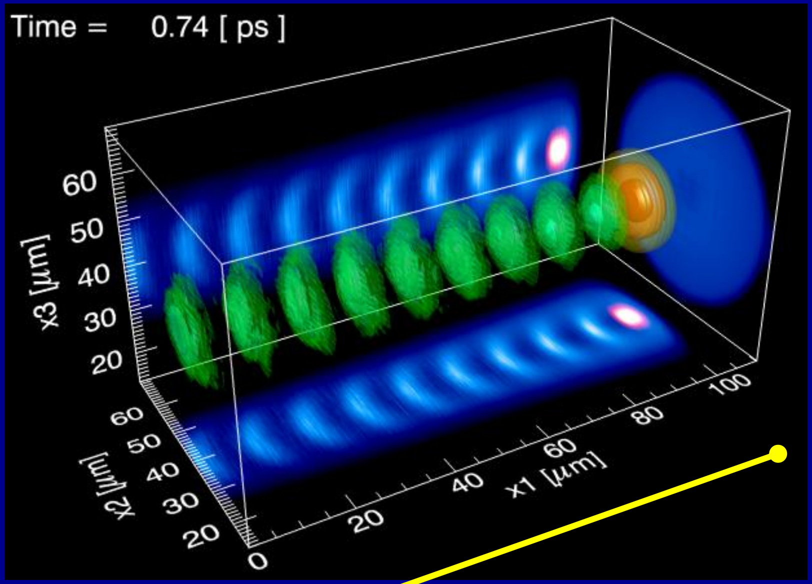
E-field$_{max}$ ≈ few 10 MeV /meter (Breakdown)
$R>R_{min}$ Synchrotron radiation

Courtesy of W. Mori & L. da Silva



1 m

RF cavity



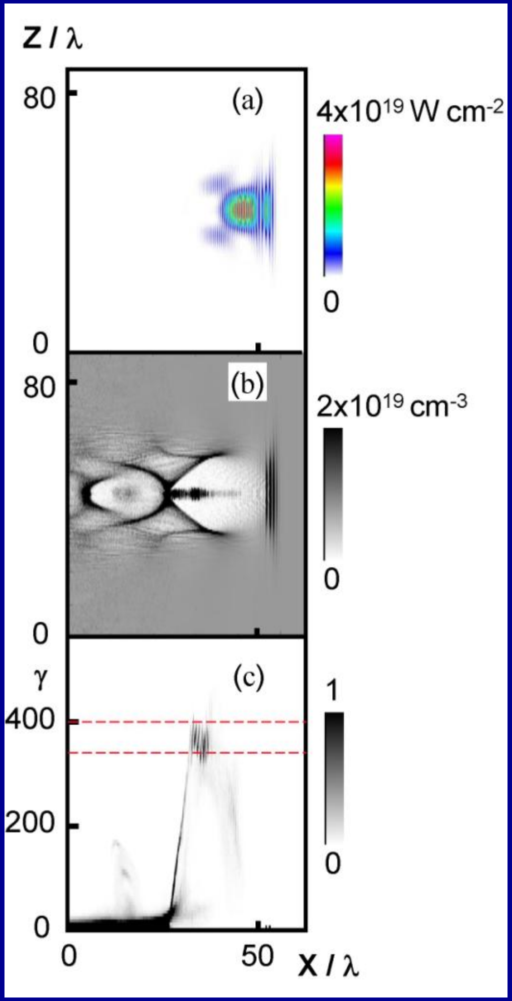
100 μm

Plasma cavity

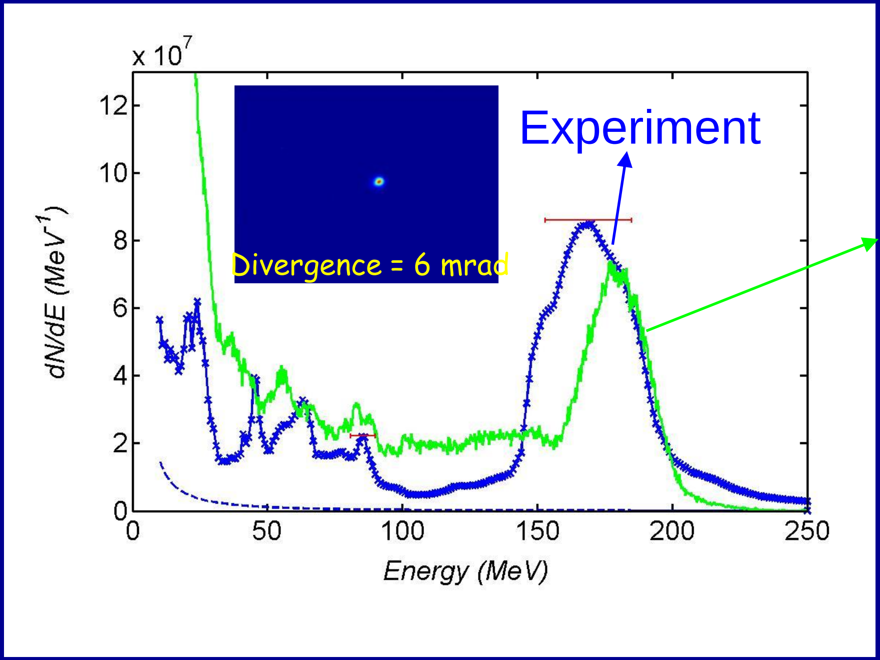
New electron acceleration mechanism

J. Faure et al., **C. Geddes et al., S. Mangles et al. ,**
in Nature 30 septembre 2004

Energy distribution improvements: The Bubble regime



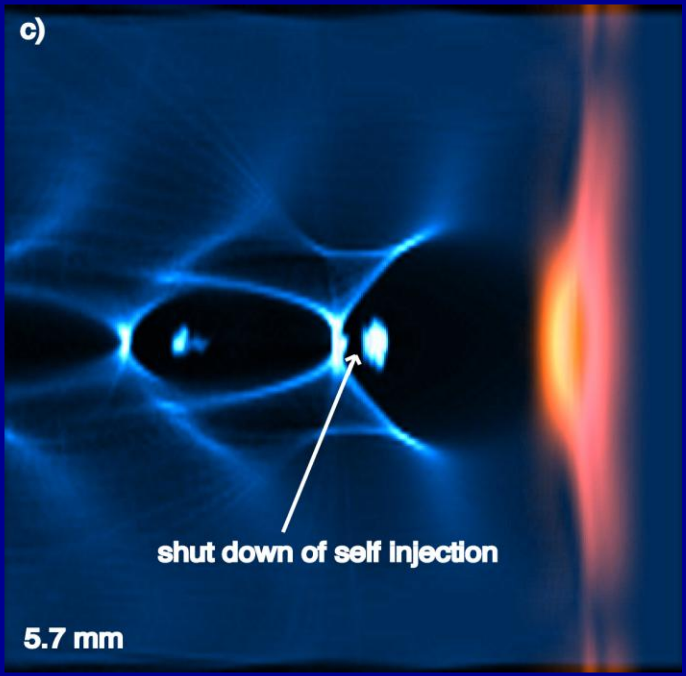
Charge in the peak : 200-300 pC

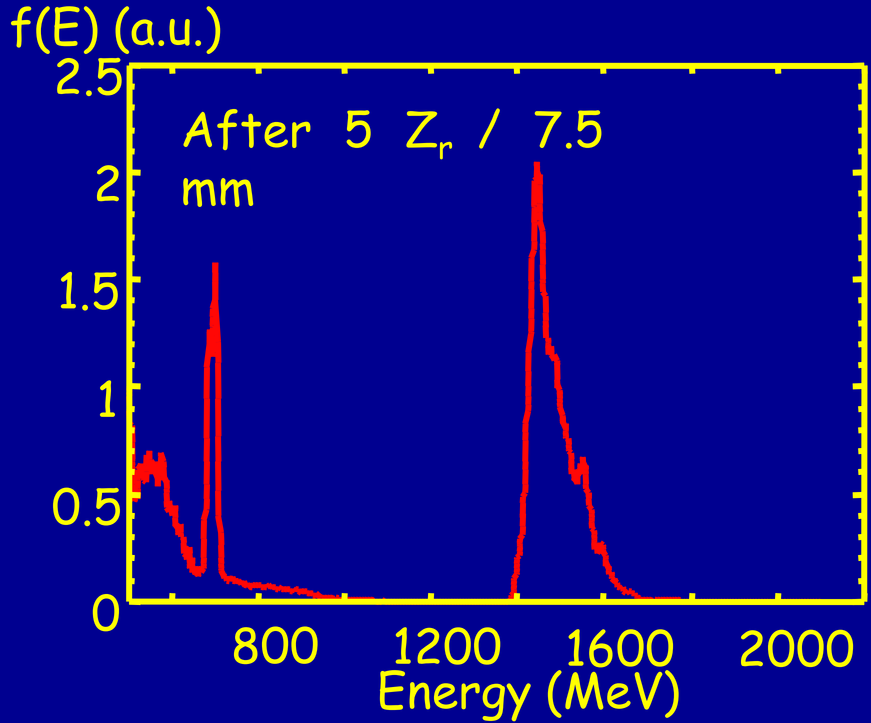


J. Faure et al. Nature (2004)

Laser plasma injector : GeV electron beams

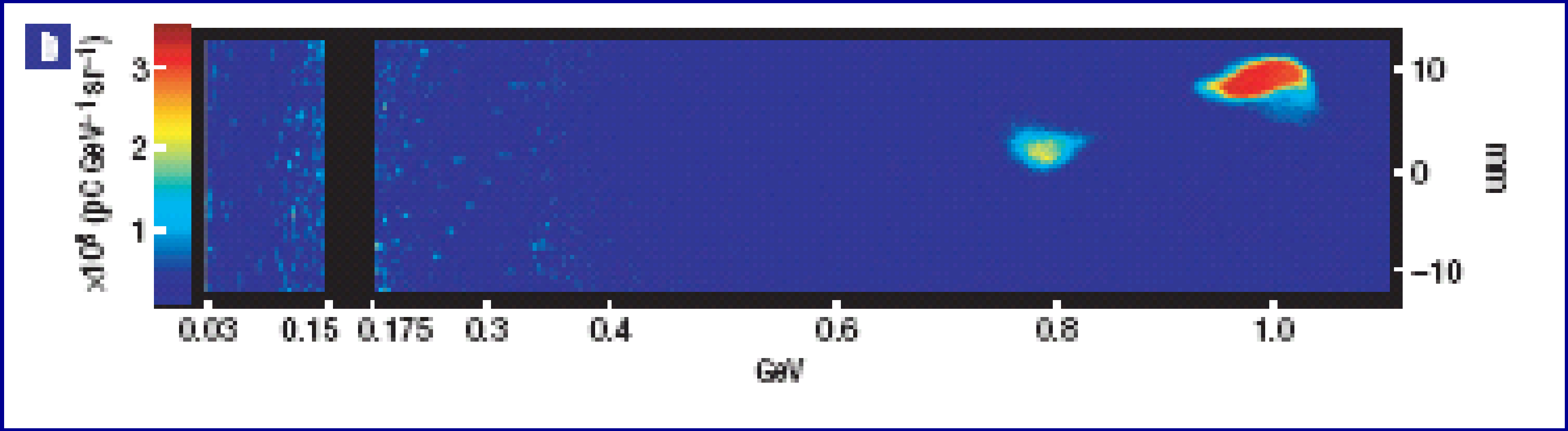
$w_0 = 20\,\mu m \quad \tau = 30\,fs \quad P = 200\,TW \quad \lambda = 0.8\,\mu m \quad a_0 = 4 \quad n_p = 1.5 \times 10^{18}\,cm^{-3}$

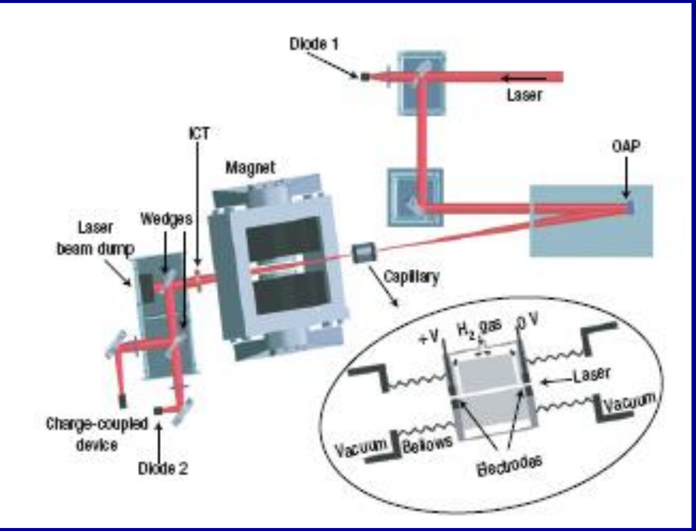




Courtesy of UCLA& Golp groups

GeV electron beams from a « centimetre-scale » accelerator





310-µm-diameter channel capillary

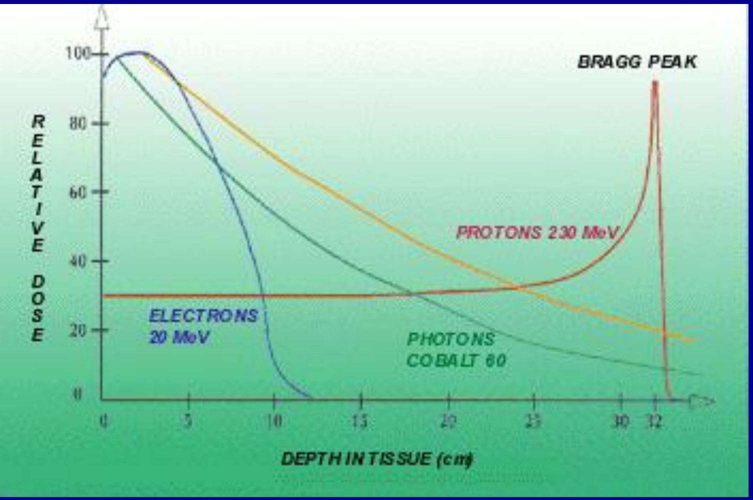
$P = 40$ TW

density 4.3×10^{18} cm^{-3}.

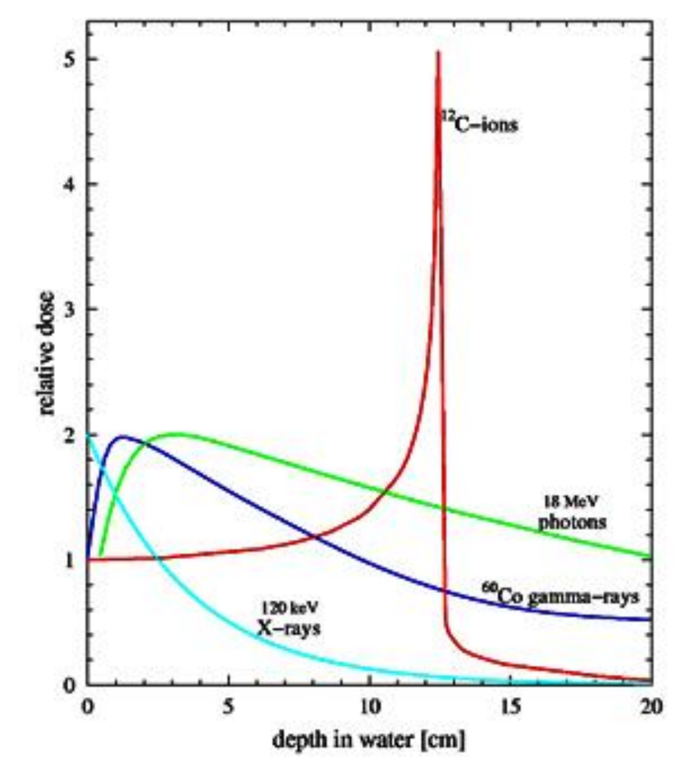
Leemans et al., Nature Physics, september 2006

ACCELERATORS FOR HADRONTHERAPY

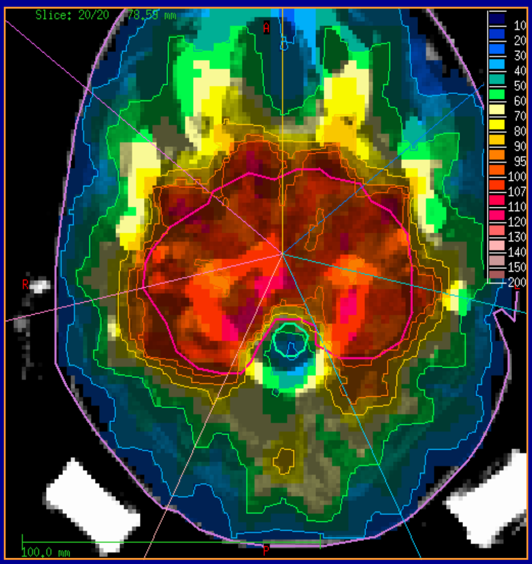
Why hadrontherapy ?



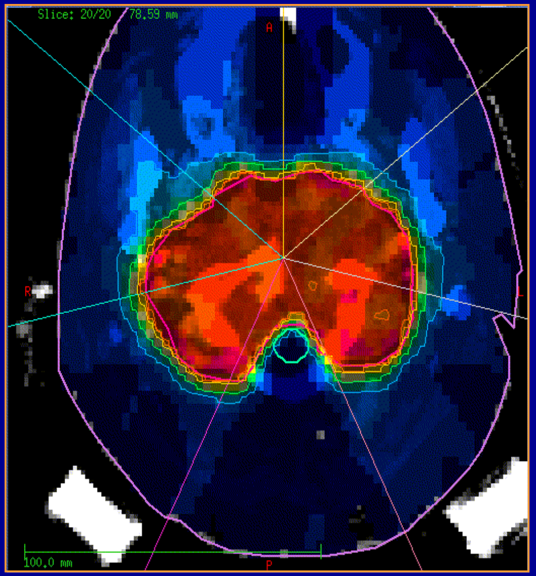
Protons deposit energy at end of motion and do not harm surrounding cells



X-rays



Protons

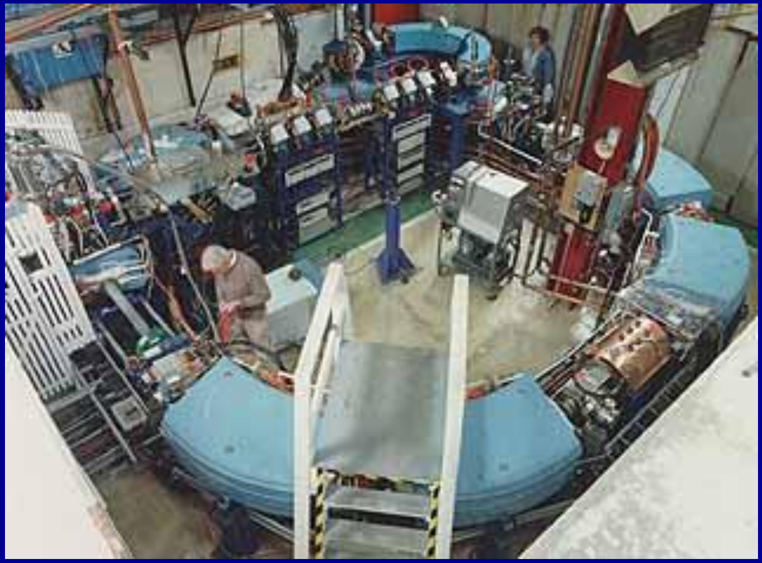


Typical hospital proton accelerators

Protontherapy accelerators are extremely big and expensive

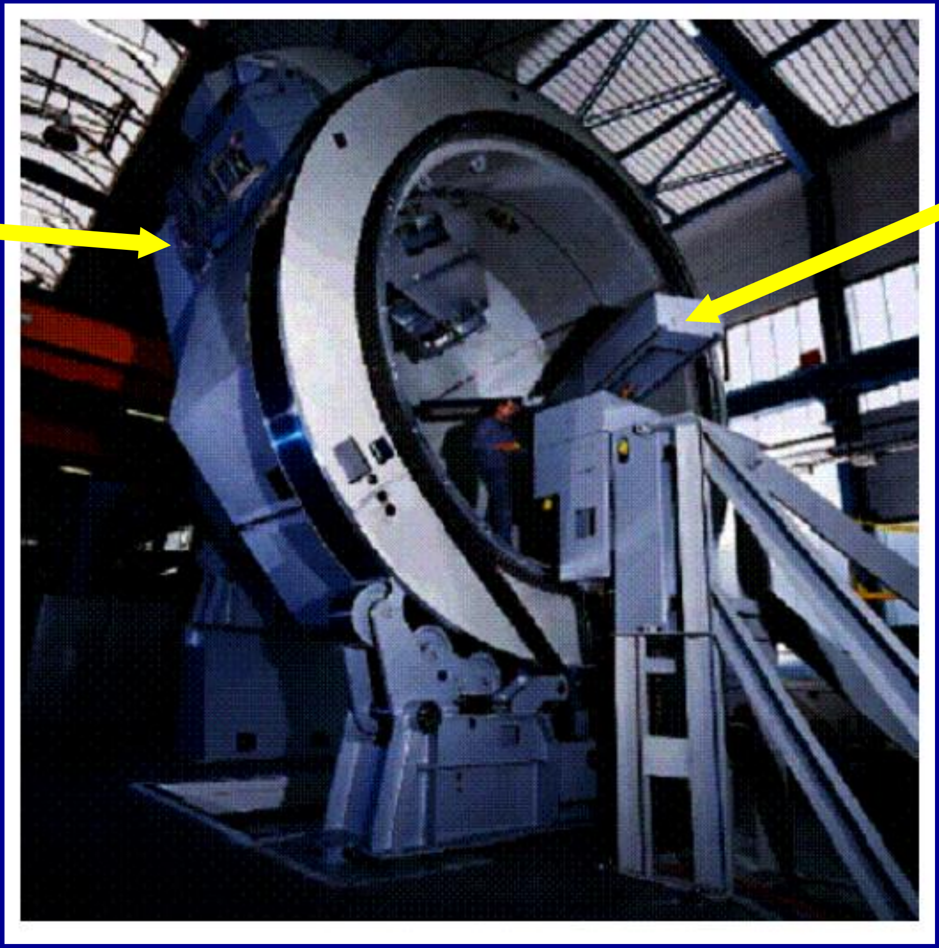
- Synchrotron (Loma Linda) :
  - max p energy : 250 MeV
  - period : 2.2 s
  - size : 12 m

- Cyclotron (IBA-NPTC) :
  - max p energy : 250 MeV
  - pulse rate : CW
  - power: 400 KW
  - size : 4 m (diameter)
  - weight : 220 tons



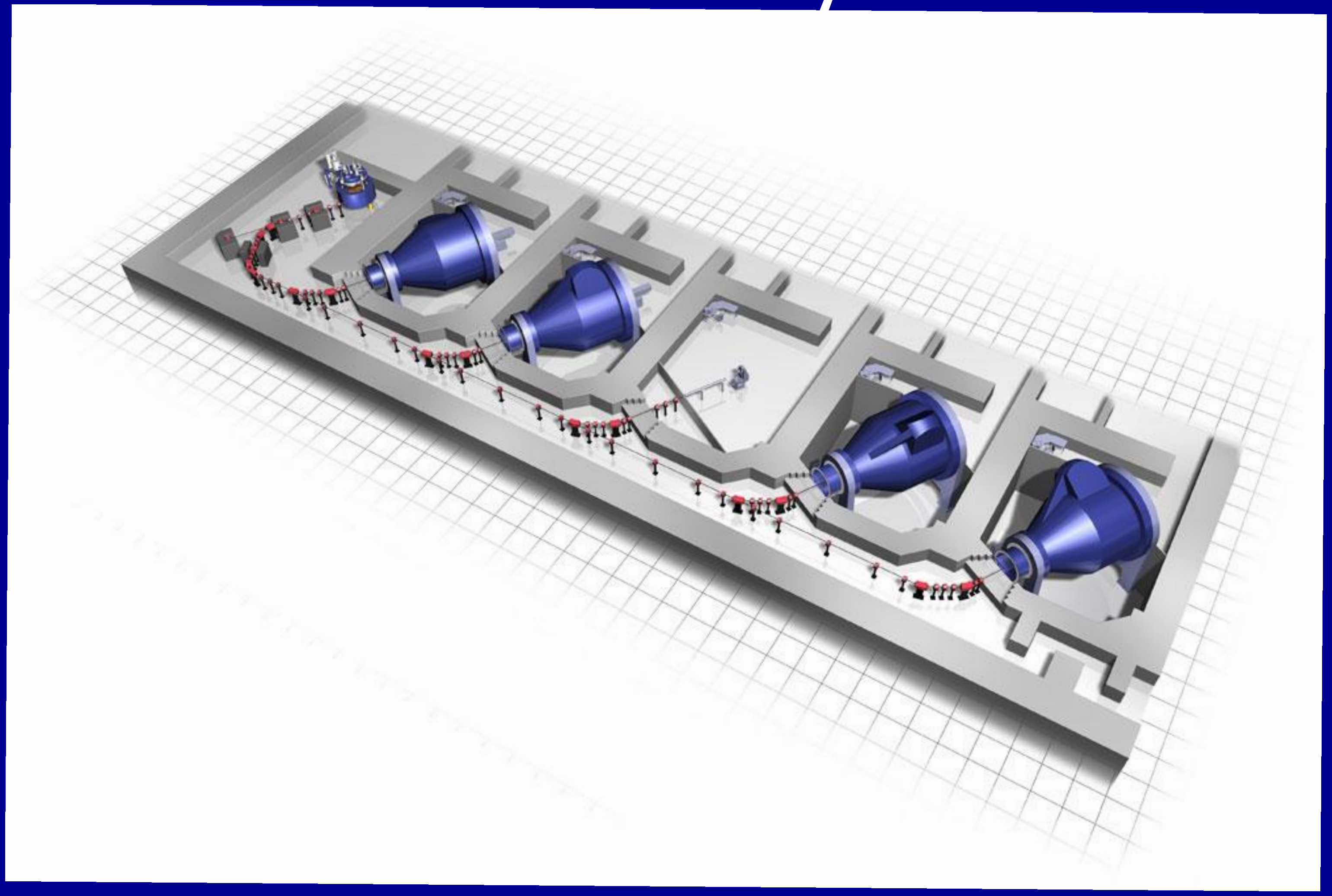
By complex gantry systems

Gantry system



Human

…require therefore a lot of space and money…



Construction costs: about 100 M€
Treatment cost (brain tumor): about 40 k€

…and are therefore rare…

Today: wordwide exist only 40 therapycenter

Year 2000: discovery of laser-generated protons

High quality and high energy protons are accelerated by high intensity lasers…

Proton beams:
- **High number**
- **High energy**
- **Very laminar**
- **Short duration**

VOLUME 85, NUMBER 14 PHYSICAL REVIEW LETTERS 2 OCTOBER 2000

Intense High-Energy Proton Beams from Petawatt-Laser Irradiation of Solids

R. A. Snavely,[1,2] M. H. Key,[1] S. P. Hatchett,[1] T. E. Cowan,[1] M. Roth,[3,*] T. W. Phillips,[1] M. A. Stoyer,[1] E. A. Henry,[1] T. C. Sangster,[1] M. S. Singh,[1] S. C. Wilks,[1] A. MacKinnon,[1] A. Offenberger,[4,*] D. M. Pennington,[1] K. Yasuike,[5,*] A. B. Langdon,[1] B. F. Lasinski,[1] J. Johnson,[6] M. D. Perry,[1] and E. M. Campbell[1]

VOLUME 85, NUMBER 8 PHYSICAL REVIEW LETTERS 21 AUGUST 2000

Energetic Heavy-Ion and Proton Generation from Ultraintense Laser-Plasma Interactions with Solids

E. L. Clark,[1,2] K. Krushelnick,[1] M. Zepf,[1] F. N. Beg,[1] M. Tatarakis,[1] A. Machacek,[3] M. I. K. Santala,[1] I. Watts,[1] P. A. Norreys,[4] and A. E. Dangor[1]

[1]Imperial College of Science, Technology and Medicine, London SW7 2BZ, United Kingdom
[2]Radiation Physics Department, AWE, Aldermaston, Reading, RG7 4PR, United Kingdom
[3]Department of Physics, University of Oxford, Oxford, OX1 3PU, United Kingdom
[4]Rutherford Appleton Laboratory, Chilton, Oxon, OX11 0QX, United Kingdom
(Received 9 November 1999)

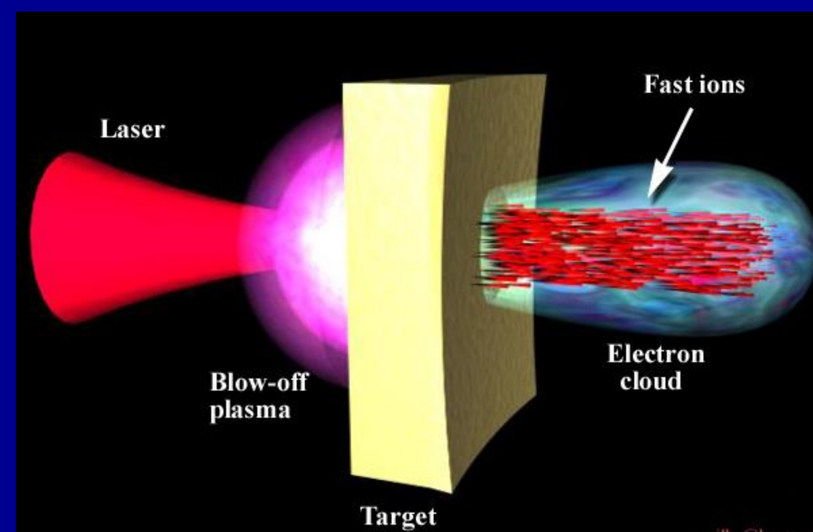
PACS numbers: 52.40.Nk, 29.30.Ep, 52.70.Nc

VOLUME 84, NUMBER 18 PHYSICAL REVIEW LETTERS 1 MAY 2000

Forward Ion Acceleration in Thin Films Driven by a High-Intensity Laser

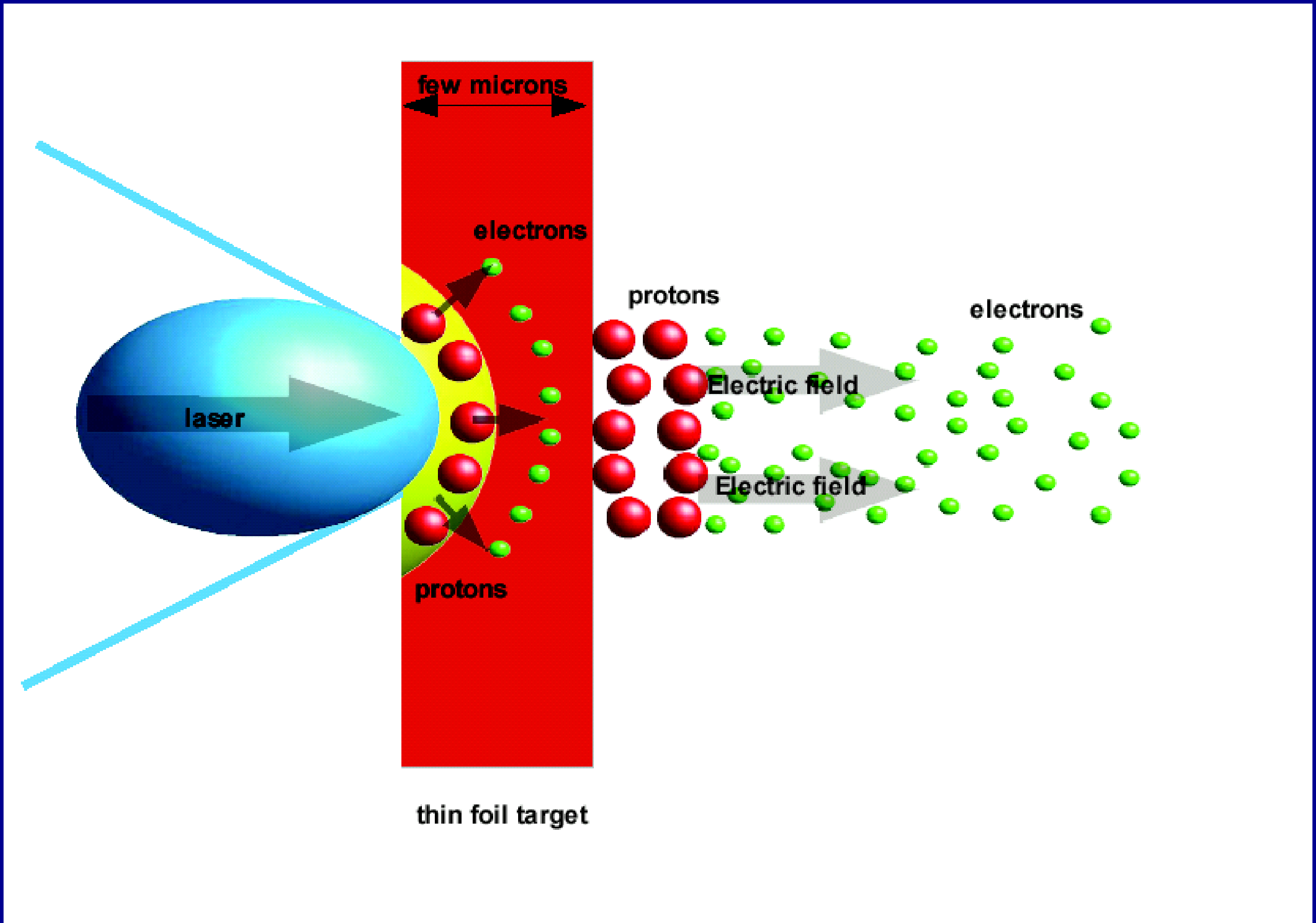
A. Maksimchuk,* S. Gu, K. Flippo, and D. Umstadter
Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, Michigan 48109-2099

V. Yu. Bychenkov[†]
Institute of Laser Engineering, Osaka University, Suita 565-0871, Japan
(Received 3 September 1999)



[Clark 2000, Krushelnick 2000, Maksimchuk 2000, Snavely 2000]

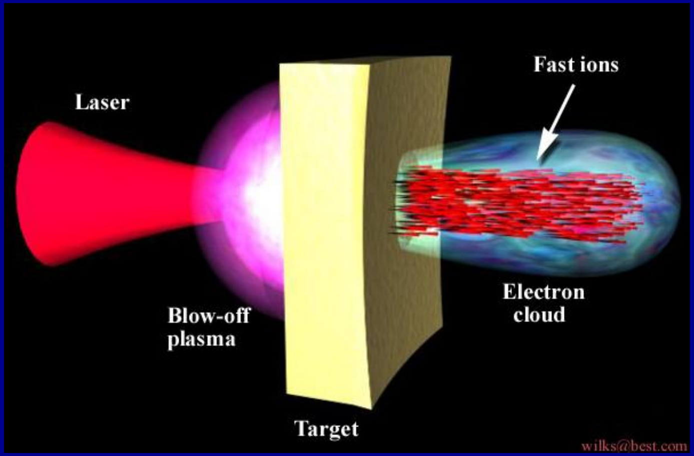
Proton generation mechanism



Since then, intensive studies on proton acceleration

Laser-acceleration 7000 more compact !!!

Acceleration takes place
in less then 1 mm



Acceleration takes place
in less then 7 m

2006: Researcher study laser-generated protons for protontherapy

ARTICLES

Laser-driven proton scaling laws and new paths towards energy increase

J. FUCHS[1,2*], P. ANTICI[1,2,3,4], E. D'HUMIÈRES[5], E. LEFEBVRE[5], M. BORGHESI[6], E. BRAMBRINK[1], C. A. CECCHETTI[6], M. KALUZA[7], V. MALKA[8], M. MANCLOSSI[8,9], S. MEYRONEINC[10], P. MORA[11], J. SCHREIBER[7], T. TONCIAN[12], H. PÉPIN[3] AND P. AUDEBERT[1]

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[7]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany
[8]Laboratoire d'Optique Appliquée –ENSTA, UMR 7639, CNRS, Ecole Polytechnique, 91761 Palaiseau, France
[9]Dipartimento di Fisica 'G.Occhialini' and INFM, Università di Milano-Bicocca, 20126 Milano, Italy
[10]Centre de Protonthérapie d'Orsay, BP 65, 91402 Orsay, France
[11]Centre de Physique Théorique, UMR 7644 CNRS-Ecole Polytechnique, 91128 Palaiseau, France
[12]Institut für Laser und Plasmaphysik, Heinrich-Heine-Universität, 40225 Düsseldorf, Germany
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Published online: 25 December 2005; doi:10.1038/nphys199

The past few years have seen remarkable progress in the development of laser-based particle accelerators. The ability to produce ultrabright beams of multi-megaelectronvolt protons routinely has many potential uses from engineering to medicine, but for this potential to be realized substantial improvements in the performances of these devices must be made. Here we show that in the laser-driven accelerator that has been demonstrated experimentally to produce the highest energy protons, scaling laws derived from fluid models and supported by numerical simulations can be used to accurately describe the acceleration of proton beams for a large range of laser and target parameters. This enables us to evaluate the laser parameters needed to produce high-energy and high-quality proton beams of interest for radiography of dense objects or proton therapy of deep-seated tumours.

Energetic proton beams with high beam quality have been produced in the last five years from thin metallic foils (usually aluminium) irradiated by ultraintense short laser pulses[1–3]. Protons accelerated from solids originate primarily from contaminant layers of water vapour and hydrocarbons on the target surface[4].

These proton beams are extremely laminar[5,6], collimated (~15° half-angle with a divergence decreasing with the beam energy) with a smooth angular distribution[7] and have a duration at the source of the order of a picosecond. Owing to these qualities, these beams are already being considered or applied in high-resolution charged-particle radiography[8], or for the production of high-energy-density matter of interest for astrophysics[9]; they could also lead to high-brightness injectors for accelerators[5] or sources for proton therapy[10–12] or radioisotope production[13].

However, these present-day sources are not yet optimized for the intended applications. The determination of the scaling laws discussed here is a necessary step to achieve this optimization. Several scaling studies have already been carried out on different facilities (from small table-top lasers to single-pulse large laser facilities)[14–21]. However, as they cannot be fully compared owing to the different sets of parameters used, no clear picture has yet emerged of the relative importance of the various target (thickness) and laser parameters (pulse energy, pulse duration, peak intensity and focal spot size).

Here we present the results of a series of experiments on aluminium foils, measuring the proton-beam maximum energy

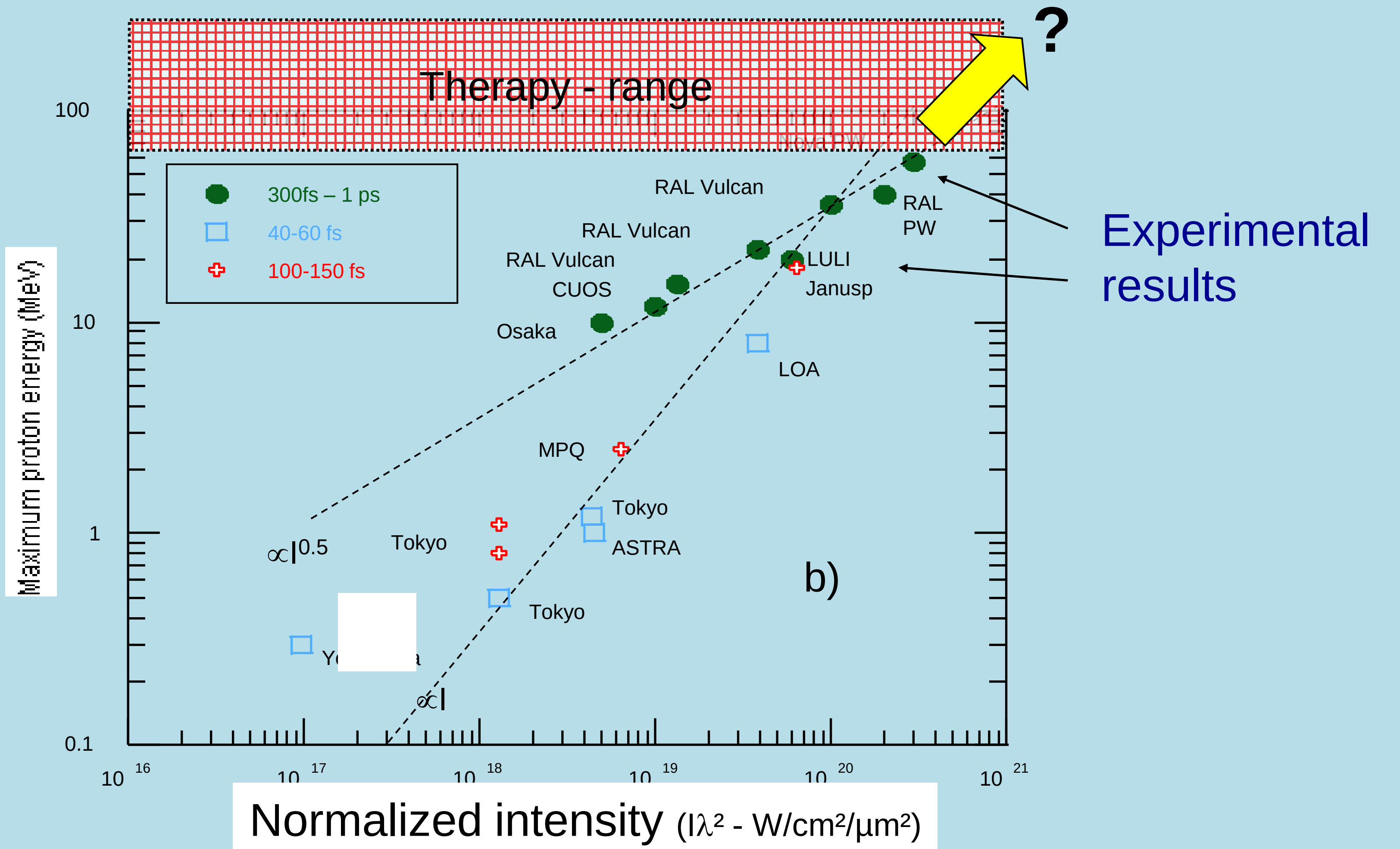
„Towards compact protontherapy ?"

„…requires very intense laser beams…"

J. Fuchs, P. Antici et al., Nature Phys 2006
P. Antici PhD thesis @ U. „Sapienza"

Projected energy

Tendency shows that intense laser can reach energies for protontherapy



What is ELI
(Extreme Light Infrastructure) ?

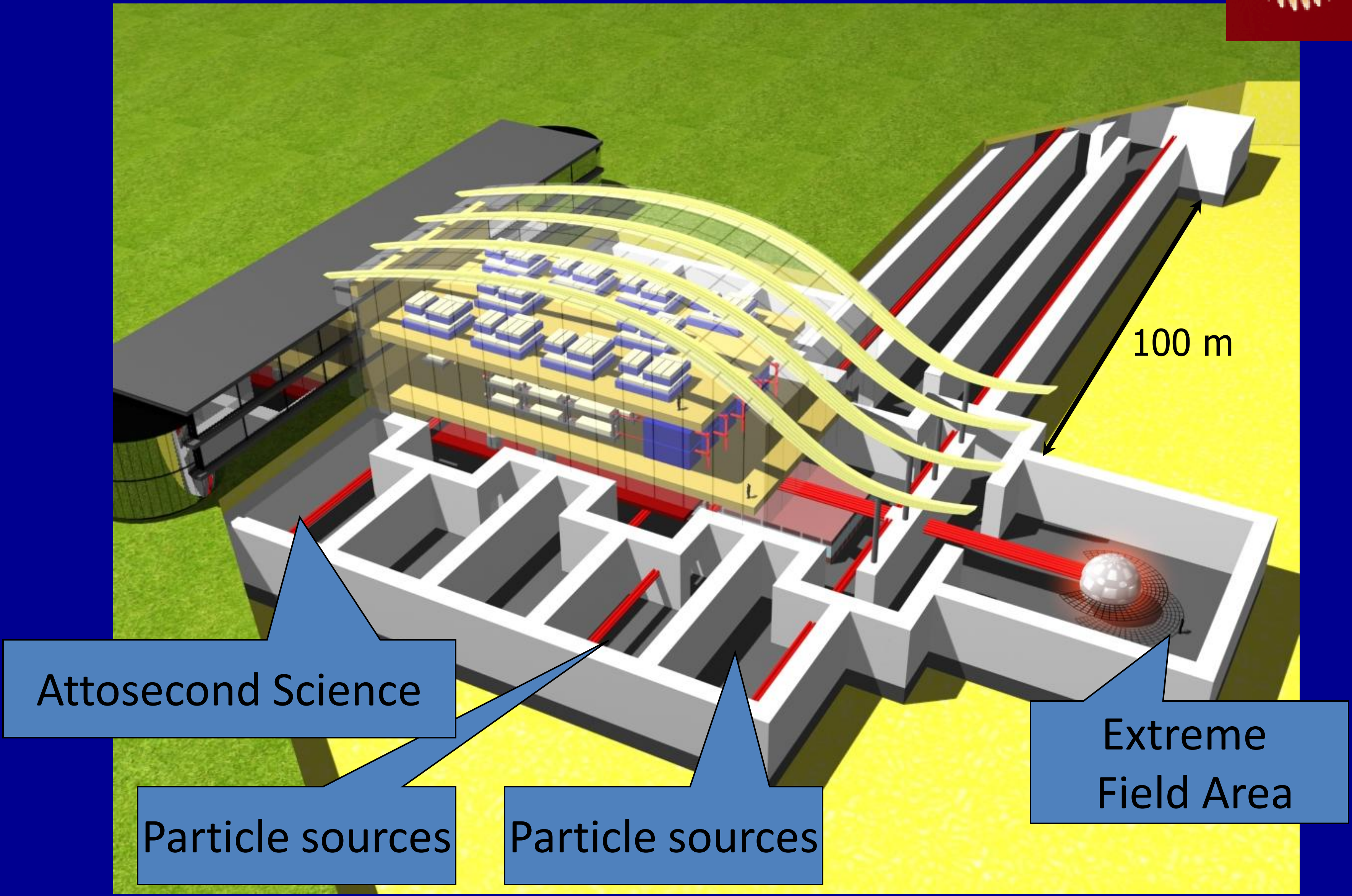
EU Project started 2007 gathering almost all laser facilities in Europe and designing the most powerfull laser.

Distributed laser facility with three pillars:

1) Czech republic (applications)
2) Hungary (attosecond science)
3) Romania (nuclear physics)

Committment: 760 M€

The Extreme Light Infrastructure exploded view

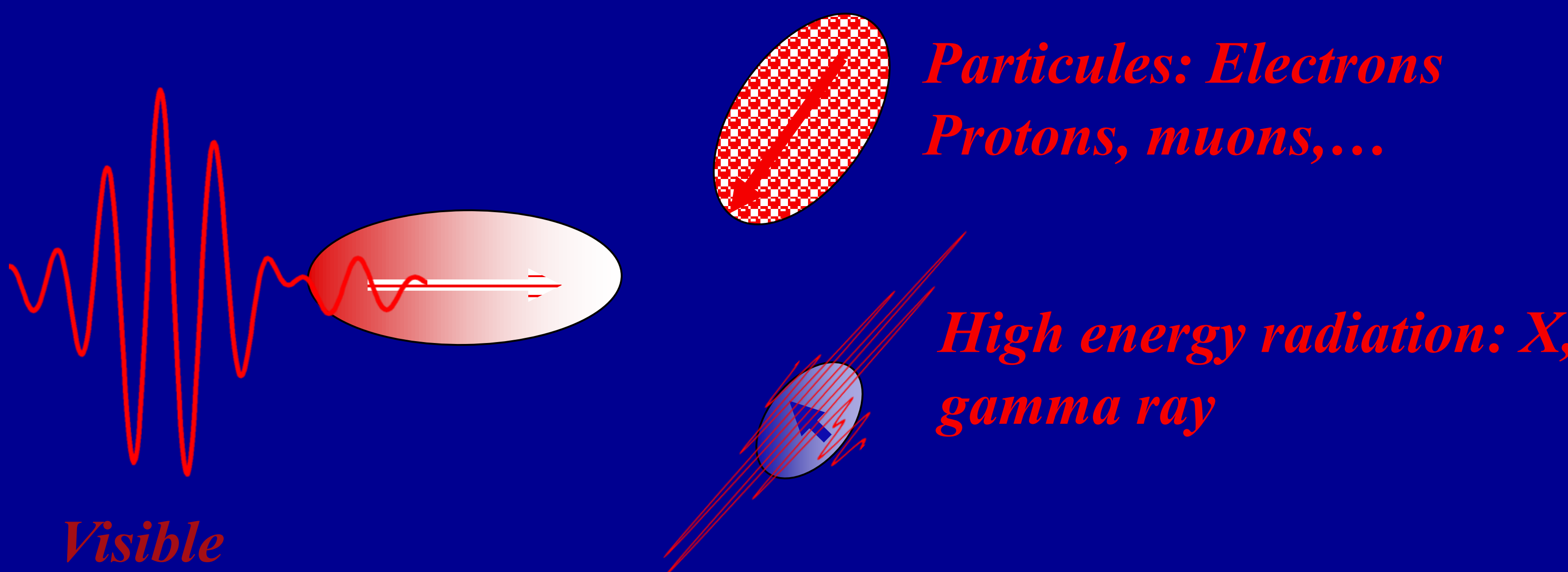


ELI: A Unique Infrastructure that offers simultaneously

- Ultra high Intensity ~10^{26}W/cm2
- High Energy particles >100GeV
- High Flux of X and γ rays
- With femtosecond time structures
- Highly synchronized

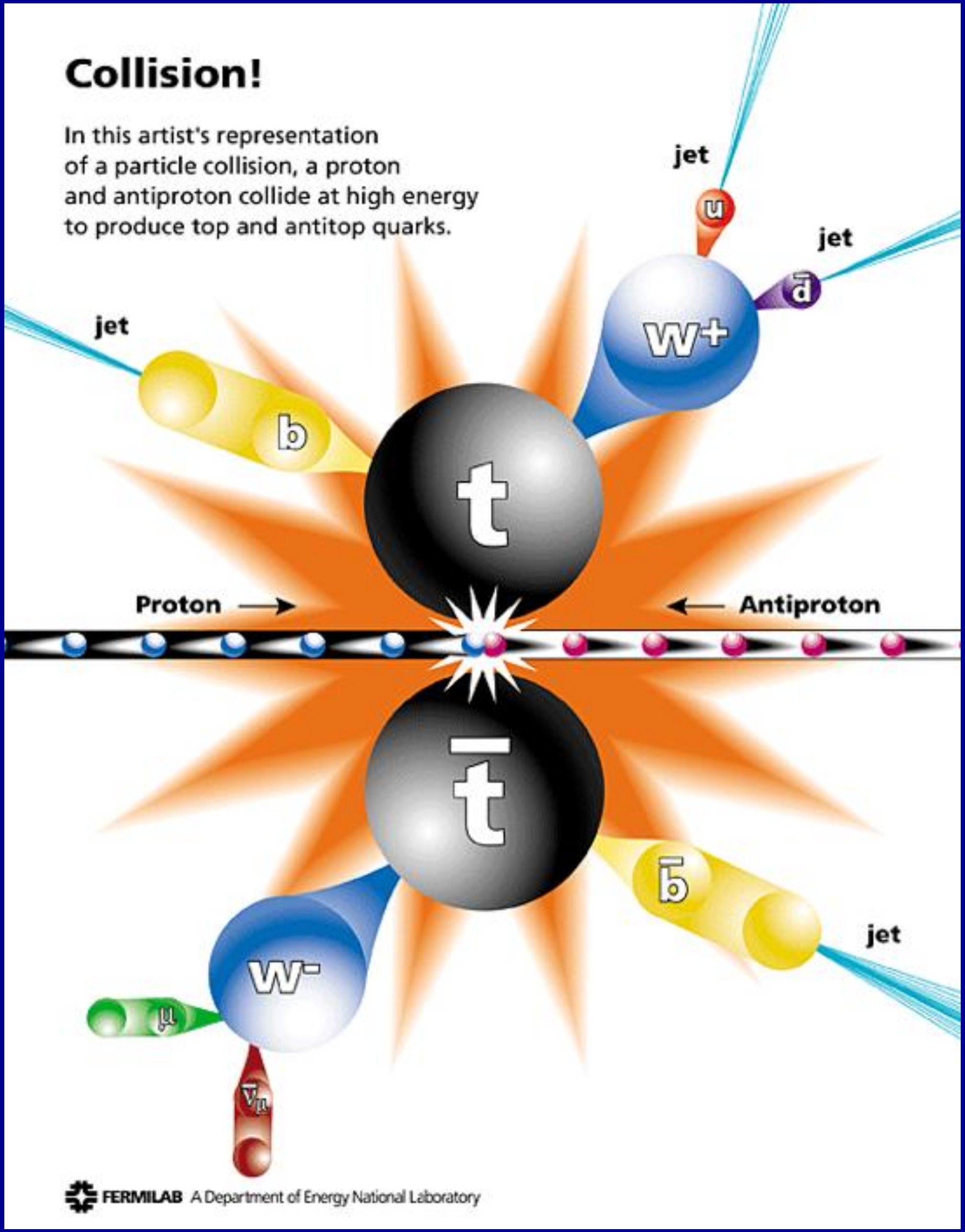
(We could possibly get beams equivalent to 10^{36} W/cm^2)

ELI will be Unique: it will provide Photons and Particles with Short and Synchronized Time Structure in the femtosecond attosecond regime



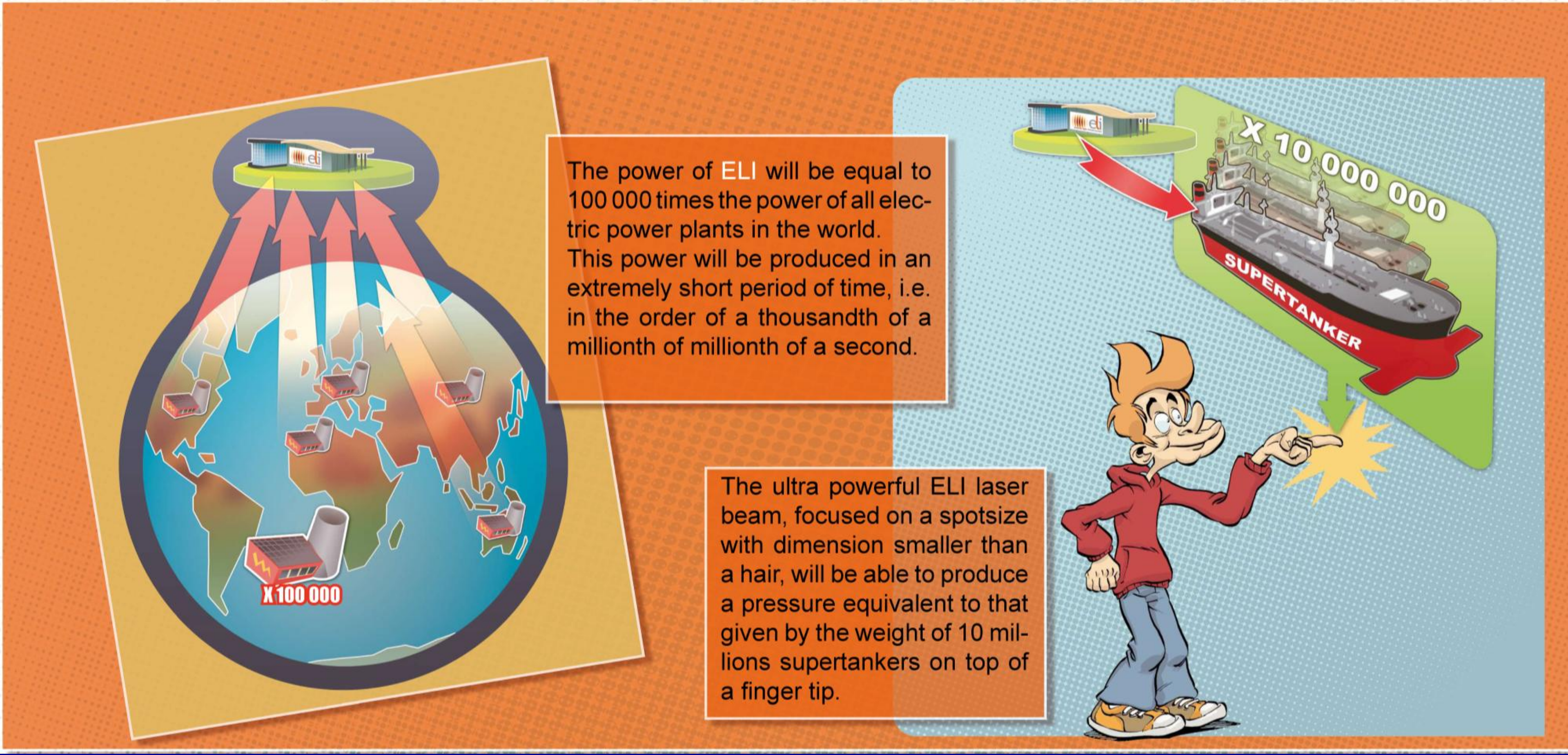
With ELI we may witness a Paradigm shift in Fundamental Physics.

Could one day Lasers Replace Accelerators?


Collision!
In this artist's representation of a particle collision, a proton and antiproton collide at high energy to produce top and antitop quarks.
jet
u
jet
d̄
W+
jet
b
t
Proton
Antiproton
t̄
b̄
jet
W-
μ
ν̄μ
FERMILAB A Department of Energy National Laboratory

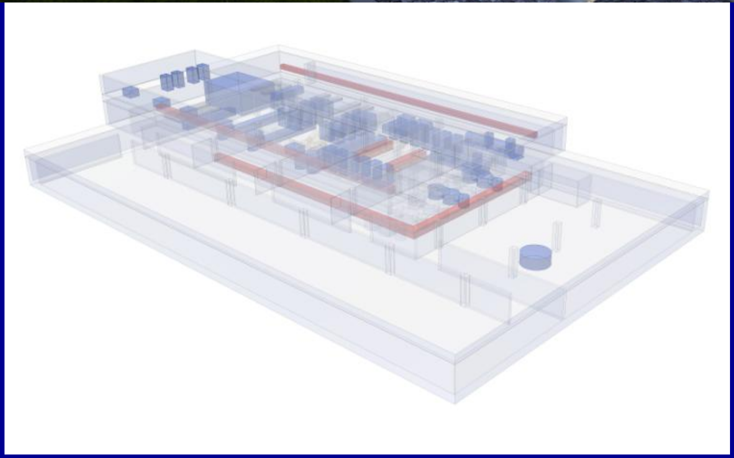
How intense will ELI be ?

ELI is supposed to deliver 200 PW,
with intermediate facilies of 20 PW



Protontherapy should be studied by the Czech pillar (Prague)

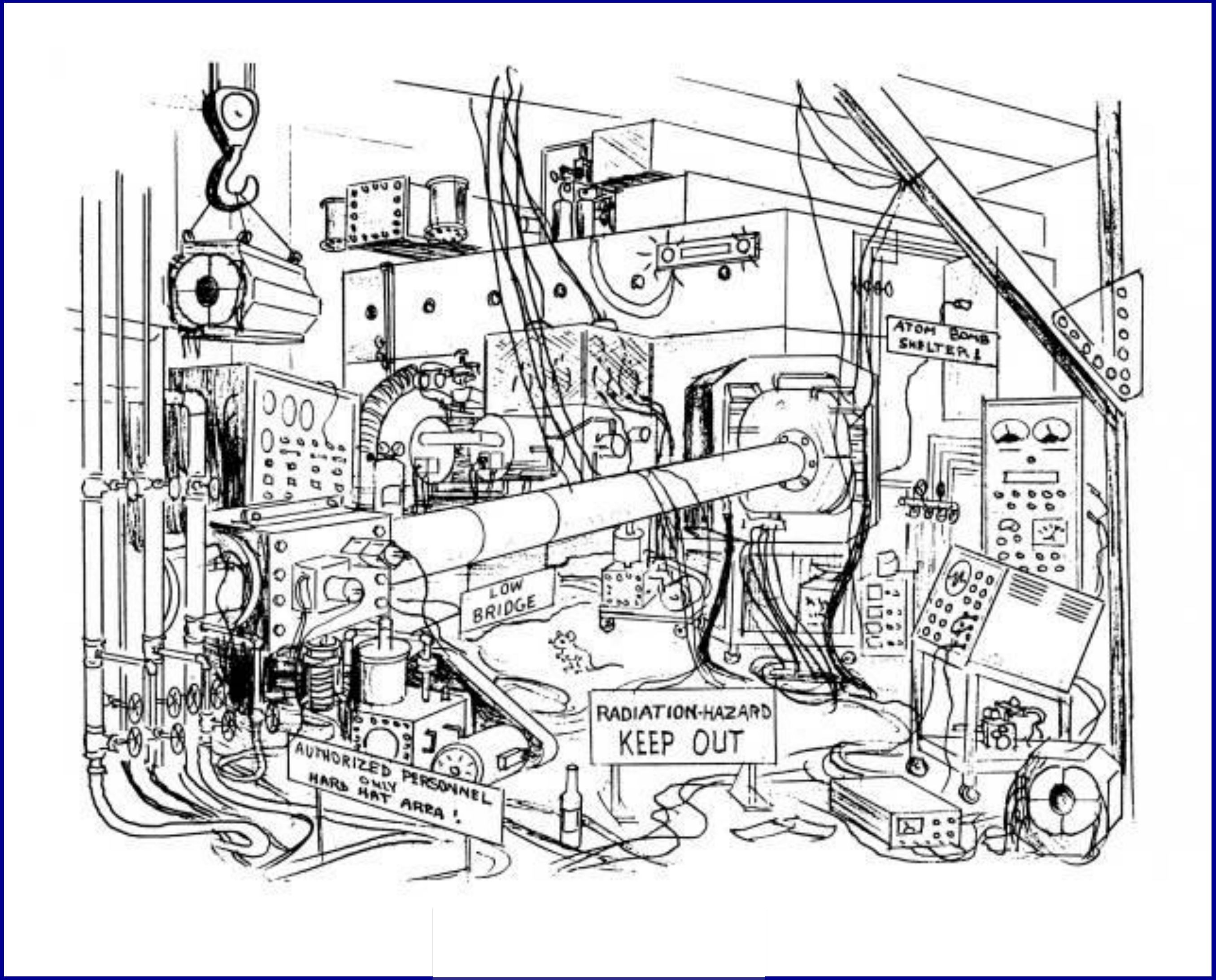
ELI-CZ will have devoted beamlines for protontherapy



CHANCES TO BE FUNDED?

A GOOD COMMUNICATION STRATEGY IS ALSO NEEDED

MODIFY THE COMMON SENSE ABOUT ACCELERATORS !!!



EXPECIALLY WITH …
THE GOVERNMENTAL FUNDING AGENCIES